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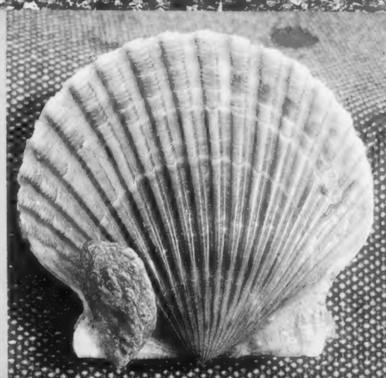

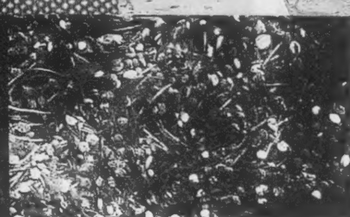

## Bay Scallops in Eastern North America: Part II

# Marine Fisheries REVIEW

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J. A. Strader, Managing Editor

On the cover:
Top to bottom, left to right—Town of Nantucket and Nantucket Harbor, Mass., courtesy of Nantucket Historical Society; shellfish law enforcement patch; northern bay scallop seed attached to small stone; scallop aquaculture harvest, C. L. MacKenzie, Jr.; eelgrass transplanted into Narragansett Bay, R. I., Jay Preshoso; bay scallop seed attached to eelgrass blades, C. L. MacKenzie, Jr.

Articles

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# The Bay Scallop, *Argopecten irradians*, in Florida Coastal Waters

WILLIAM S. ARNOLD

## Introduction

The bay scallop, *Argopecten irradians*, supports one of the most popular and family-oriented fisheries currently pursued in Florida coastal waters. Harvesting bay scallops has a long history in both peninsular (Marelli and Arnold, 2001) and panhandle (Mikell, 1992; 1994; Thomas and Campbell, 1993) Florida dating to at least A.D. 900, but in recent years the popularity of the scallops as a target for recreational and commercial fishermen appears to have contributed to local declines and the implementation of more stringent management measures (Arnold et al., 1998).

Those declines also have instigated many efforts to rebuild scallop populations by transplantation of field-collected specimens or by rearing scallops in a hatchery setting and then planting them at sites targeted for restoration (Arnold et al., 2005). Regardless of the methods used to restore scallop populations in Florida, the species remains imperiled in the face of continued human population growth and concomitant loss of suitable bay scallop habitat.

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*ABSTRACT—The bay scallop,* Argopecten irradians, *supported a small commercial fishery in Florida from the late 1920's through the 1940's; peak landings were in 1946 (214,366 lbs of meats), but it currently supports one of the most popular and family-oriented fisheries along the west coast of Florida. The primary habitat of the short-lived (18 months) bay scallop is seagrass beds. Peak spawning occurs in the fall. Human population growth and coastal development that caused habitat changes and reduced water quality probably are the main causes of a large decline in the scallop's abundance. Bay scallop restoration efforts in bays where they have become scarce have centered on releasing pediveligers and juveniles into grass beds and holding scallops in cages where they would spawn.*

## Life History

Bay scallops are short-lived, and in Florida their life span rarely exceeds 18 months (Barber and Blake, 1985). Their primary habitat is seagrass beds, particularly *Thallassia* and *Syringodium*, but it is not uncommon for scallops to be found in open sand areas or lying on algal mats among the seagrass beds. Bay scallops may or may not have the physiological apparatus to support gregarious behavior, but they are commonly found in patches that are densely populated relative to background abundance. The patchy distribution pattern may facilitate successful reproduction. Scallops are broadcast spawners, so the likelihood of successful fertilization is enhanced by proximity (Levitan, 1995).

Peak spawning activity appears to occur in the fall season in Florida, in contrast to the situation with bay scallops in New York to Massachusetts where spawning is a summer or even spring event. However, ongoing studies by the author show that spring spawning occurs in some years, and recruitment has been recorded in almost every month of the year. Fertilized larvae spend about two weeks in the pelagos, after which they settle and attach to seagrass blades. At a shell height of about 15–20 mm, the scallops drop off the grass blades and assume a benthic existence. They achieve a shell height of 50–55 mm by June of the following year, at which time growth slows considerably and energy is devoted to reproductive development and spawning (Barber and Blake, 1983).

## Species Distribution and Status

Three species of *Argopecten* occur in Florida including the calico scallop, *Argopecten gibbus*; the nucleus scallop, *Argopecten nucleus;* and the bay scallop, *Argopecten irradians* (Abbott, 1974). The calico scallop inhabits deeper offshore waters and has been the target of an occasionally lucrative commercial fishery (Moyer and Blake, 1986; Blake and Moyer, 1991). In contrast, the bay scallop and the nucleus scallop inhabit shallow inshore waters. Their range appears to overlap in south Florida and particularly Biscayne Bay (Waller, 1969), but otherwise the range of the nucleus scallop is more southerly than that of the bay scallop.

Nucleus scallops occur throughout the Caribbean and northern South America (Waller, 1969) whereas the most southerly record of the bay scallop is from Tuxpan in the Veracruz region of Mexico (Wakida-Kusunoki, 2009). There are published reports of calico scallops occurring in Biscayne Bay (Coleman et al., 1994), thus creating a situation where all three species co-occur, and the author has many records of calico scallop recruits collected from inshore bays on both the east and west coast of Florida.

Within the species *Argopecten irradians*, three extant subspecies are recognized including *A. i. irradians* from the northeastern United States, *A. i. concentricus* from the Mid-Atlantic

region and eastern Gulf of Mexico, and *A. i. amplicostatus* from the western Gulf of Mexico including Mexico. A fourth subspecies (*A. i. taylorae*) occupying Florida and the eastern Gulf of Mexico has been suggested but not codified (Marelli et al., 1997a). If that subspecific designation is accepted, then the *A. i. concentricus* designation would be dropped and bay scallops from North Carolina north would be lumped into the *A. i. irradians* group (Marelli et al., 1997b).

The three subspecies are in many respects similar in appearance although they can be distinguished by morphological details such as hinge width and the number of ribs on the shell surface (Waller, 1969). They also share a dependence on marine seagrass as a habitat (Thayer and Stuart, 1974), although the particular species of seagrass upon which the scallop depends differs from site to site according to seagrass distribution patterns. That dependence upon seagrass has contributed to the decline of bay scallops in Florida and throughout the range of the species, because the seagrasses are becoming scarcer.

Museum collections indicate that the distribution of bay scallops in Florida once extended from Palm Beach on the southwest coast of the state to Pensacola and westward to the Chandeleur Islands in Louisiana (Waller, 1969). Although no definitive information is available, it is likely that the scallops were not continuously distributed within this range. Instead, the population was composed of many discretely distributed subpopulations that inhabited the bays and estuaries that characterize the Florida coast. In recent years, many of those local populations have disappeared in response to a variety of factors including habitat loss, deteriorating water quality, and overfishing.

According to Arnold et al. (1998), by the mid 1990's only two consistently productive local populations remained in Florida, one located in the coastal waters near Steinhatchee and the other located within St. Joseph Bay (Fig. 1). The loss of these local populations appears to have occurred from south to north, somewhat consistent with human development patterns in the state. Bay scallops appear to have disappeared first from the southeast coast of the state, then from Pine Island Sound in southwest Florida, followed by loss of populations in Sarasota Bay and Tampa Bay, then Anclote, and finally Homosassa and Crystal River (Fig. 1). However, bay scallops also have disappeared from western panhandle Florida, suggesting a more complex pattern of loss.

Anecdotal information gleaned from telephone and personal interviews with fishermen, owners of marine-dependent businesses (dive shops, bait shops, marinas), and coastal managers conducted during 1991, 1992, and 1993 supports the pattern of disappearance described above (Arnold and Marelli[1]). Responses were divided into three geographically representative areas including southwest Florida (from Tampa Bay south), the central west coast of Florida (i.e. the Big Bend, from Tampa Bay north to approximately Apalachicola Bay), and northwest Florida (from Apalachicola Bay to the Florida–Alabama state line).

In the southwest region, scallops were reported only from Pine Island Sound, where they were scarce and their interannual abundance was inconsistent. In the central region, scallops were rare from Tampa Bay north to the Pepperfish Keys area, but from Pepperfish Keys north to Keaton Beach (i.e. the Steinhatchee area) scallops were abundant, although abundance varied from year to year. Respondents reported that scallops "used to be" abundant in areas such as Anclote and Homosassa and suggested that declines in these populations were relatively recent.

In the northwest region, scallops remained abundant in St. Joseph Bay and occasionally could be found in St. Andrew Bay, but otherwise they had largely disappeared from the area. Various explanations were offered by the respondents for any observed declines, including increased turbidity, overfishing, and wet weather during the spring, but no definitive correlations could be discerned.

Bay scallop population density surveys were initiated at several sites along the Gulf of Mexico coast of Florida beginning in 1993 and have continued to the present. Survey sites were selected based upon the historical and anecdotal information described above and have been continued (and expanded) since their initiation at Homosassa in 1993.

At each survey site, 20 stations were randomly selected from within the 2 ft to 6 ft (0.61 m to 1.83 m) depth contours (Arnold et al., 1998). At each station, two scuba divers swam the length of a 984 ft (300 m) transect line and counted all scallops within 1.1 yds (1 m) on either side of the line, thus surveying an area of 718 yds$^2$ (600 m$^2$) at each station or 14,352 yds$^2$ (12,000 m$^2$) at each site. At the Cedar Key site, where the extent of seagrass beds is relatively small, only 6 rather than 20 stations were surveyed each year.

Initial survey results supported the historical and anecdotal information reported above. Scallops have been essentially nonexistent in Pine Island Sound (Table 1) in southwest Florida and in Pensacola Bay and St. Andrew Bay in northwest Florida. In the central region, scallops were rare in the Homosassa/Crystal River area through 1998 but abundance has been highly variable in Anclote. In contrast, although interannual fluctuations are apparent at both the St. Joseph Bay and Steinhatchee study sites, at least through 1998 scallop abundance at those sites has been an order of magnitude greater than at most other sites during most years. Since 1998, some increases in scallop abundance at several sites have occurred. Events that may have contributed to the increases are discussed in the "Population Restoration Efforts" section below.

### Causes of Population Loss

There appears to be no single explanation or event that led to the depletion of bay scallops in coastal Florida. The available explanations are based largely upon anecdotal information rather than hard data. In southeast Florida, where

[1]Arnold, W. S., and D. C. Marelli. 1991. Assessment of bay scallop populations on the west coast of Florida. Internal Report IHR1991-001, Fla. Mar. Res. Inst., 19 p.

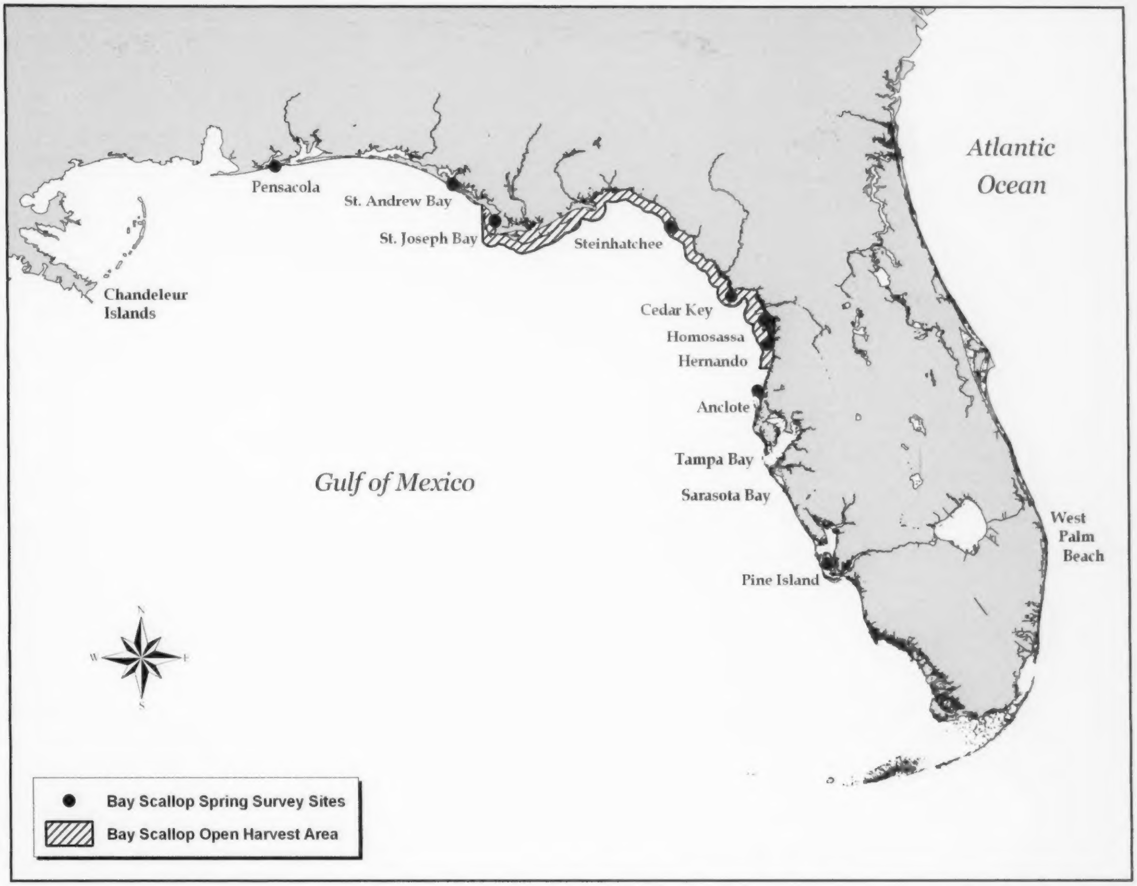


Figure 1.—Bay scallops, *Argopecten irradians*, in Florida, including their historic range from West Palm Beach to the Chandeleur Islands in Louisiana, the location of summer adult abundance survey sites, and the present (2009) open recreational harvest area along the west coast.

**Table 1.—Mean abundance of adult bay scallops, *Argopecten irradians*, at various sites along the Florida west coast. Sample locations are depicted in Figure 1. Adult abundance (SD) is calculated as the mean of the abundance at each of twenty 718 yd$^2$ (600 m$^2$) survey transects determined by scuba divers, except at Cedar Key where only six stations were surveyed each year.**

| Site | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Pine Island | | 0 | 2.4 | 0.8 | 2.3 | 2.4 | 2.6 | 2.8 | 5.5 | 0.6 | 0.6 | 1.0 | 93.4 | 8.2 |
| | | (0) | (7.7) | (2.1) | (3.9) | (5.7) | (6.1) | (5.3) | (10.5) | (1.6) | (1.1) | (1.8) | (131.9) | (9.0) |
| Anclote | | 14.6 | 0.2 | 3.4 | 47.4 | 20.3 | 2.5 | 22.2 | 5.9 | 37.2 | 35.8 | 2.8 | 26.4 | 11.8 |
| | | (26.8) | (0.7) | (5.8) | (74.0) | (69.8) | (3.8) | (52.3) | (8.0) | (63.7) | (49.8) | (7.4) | (34.9) | (16.3) |
| Hernando | | | | | 14.2 | 0.6 | 5.7 | 42.2 | 46.1 | 7.2 | 8.0 | 3.3 | 17.4 | 6.6 |
| | | | | | (33.1) | (1.5) | (11.8) | (44.9) | (124.2) | (3.9) | (16.8) | (6.0) | (51.7) | (14.3) |
| Homosassa | 7.3 | 6.8 | 4.7 | 3.2 | 15.2 | 3.0 | 28.6 | 242.8 | 299.3 | 51.8 | 125.6 | 5.7 | 72.3 | 21.9 |
| | (6.3) | (9.8) | (6.4) | (2.7) | (16.0) | (7.9) | (48.1) | (290) | (305.4) | (38.9) | (149.8) | (13.2) | (90.9) | (21.3) |
| Cedar Key | | | | | | 0.8 | 2.7 | 0.3 | 7.7 | 2.3 | 6.0 | 0.0 | 4.7 | 3.8 |
| | | | | | | (1.2) | (2.8) | (0.5) | (9.4) | (2.6) | (4.2) | (0.0) | (7.7) | (6.0) |
| Steinhatchee | | 153.4 | 29.2 | 250.2 | 25.9 | 27.3 | 164.4 | 218.3 | 122.8 | 138.7 | 61.3 | 18.2 | 22.7 | 11.2 |
| | | (159.0) | (68.3) | (414.6) | (35.0) | (38.2) | (227.3) | (388.5) | (190.0) | (136.9) | (62.1) | (42.1) | (23.4) | (14.5) |
| St. Joseph Bay | | 35.8 | 132.2 | 247.7 | 27.3 | 13.4 | 31.1 | 3.8 | 12.1 | 37.5 | 28.7 | 2.4 | 59.3 | 35.6 |
| | | (81.9) | (175.5) | (312.2) | (41.5) | (21.3) | (48.2) | (6.3) | (37.6) | (55.2) | (48.2) | (5.6) | (118.3) | (43.0) |
| St. Andrew Bay | | 56.8 | 5.8 | 20.1 | 1.8 | 2.2 | 2.4 | 1.2 | 0.1 | 7.8 | 6.6 | 1.4 | 9.4 | 0.4 |
| | | (70.8) | (5.8) | (34.8) | (2.7) | (6.9) | (3.0) | (2.6) | (0.2) | (11.5) | (18.3) | (3.1) | (11.8) | (1.0) |
| Pensacola Bay | | | 0.0 | | | | | | | 0.2 | 0.6 | 0.0 | 0.0 | |
| | | | (0.0) | | | | | | | (0.4) | (1.3) | (0.0) | (0.0) | |

bay scallops occurred at least during the early part of the century (see "Fishery and Harvest Regulations" section below), intensive human population growth and concomitant development have led to obvious and substantial changes to habitat and water quality that certainly contributed to the scallop's decline.

In southwest Florida, construction of a causeway from the mainland to Sanibel Island is popularly considered to be the causative agent of decline of the Pine Island Sound scallop population. However, Dr. Peter Sheng[2] at the University of Florida suggests that, based upon his hydrodynamic modeling of Pine Island Sound, dredging the Intracoastal Waterway through Pine Island Sound led to increased transport of fresh water north from the Caloosahatchee River into the sound rather than south into the Gulf of Mexico.

Since the Sanibel Causeway lies just south of the mouth of the Caloosahatchee River and likely contributes to blocking the exit of fresh water from the river into the Gulf of Mexico, it is possible that channelization and causeway construction acted synergistically to increase freshwater inputs into Pine Island Sound. The increase in fresh water would lower the sound's salinity and thereby reduce the suitable bay scallop habitat, because scallops require salinities above 20‰ for proper embryological and larval development (Castagna, 1975).

In Tampa Bay, it is likely that dredge-and-fill operations, causeway construction, and human population growth indirectly contributed to the depletion of scallops in that estuary. Those activities led to a loss of about 80% of the seagrass beds in Tampa Bay (Lewis et al., 1985). Such a loss of essential scallop habitat (Thayer and Stuart, 1974) would probably result in an equivalent or greater loss of scallops. The loss of the Tampa Bay scallop population may have imperiled other populations along the west coast of Florida, because that estuary may have acted as a source of larvae for periodic resupply of populations both north and south of Tampa Bay.

The depletion of scallop populations in the Anclote and Homosassa/Crystal River area may be the result of indirect effects that contributed to a lack of larval supply to these areas. Scallops are an annual species in Florida, so extreme population fluctuations occur. It is therefore not the collapse in abundance that is of concern but rather the lack of recovery. When bay scallop populations fall below a certain level of abundance, they appear to be no longer capable of producing enough larvae to support self-seeding (Arnold et al., 1998).

At that point, allochthonous larval inputs are necessary to rebuild the population, but as the external sources of such larvae are lost (e.g. as scallop populations in Tampa Bay and other areas become depleted) the likelihood of larval supply is lessened. A "domino effect" comes into play; as more populations are lost the remaining populations become increasingly imperiled. This concept of population collapse, based upon the theory of metapopulation ecology (Levins, 1969; Hanski, 1991) has formed the basis of bay scallop population restoration efforts in Florida.

### Population Restoration Efforts

Efforts to rebuild bay scallop populations in Florida have been ongoing on a sporadic basis since at least the 1970's, but a more concerted effort was initiated by Dr. Norman J. Blake at the University of South Florida beginning in the early 1990's (Blake, 1996; 1998; Lu and Blake, 1997). Those efforts involved culturing locally collected scallops in a hatchery setting (Lu and Blake, 1997), then either releasing the resulting juveniles into grass beds or planting them into cages deployed throughout Tampa Bay (Blake, 1996; 1998).

Bay scallop population restoration efforts in Florida were expanded in 1997 to include several additional locations including Anclote, Homosassa, and Crystal River (Arnold et al., 2005). For the latter effort, ten stations were established within each of the Tampa Bay, Anclote, Homosassa, and Crystal River study areas and from 50–300 scallops were planted in each of five cages at each of those stations. Scallops planted in spring at a shell height of about 20 mm grew slowly and did not achieve full adult shell height until the following spring, but they did appear to develop and spawn normally.

Plantings were conducted in 1998, 1999, and 2000, and contemporaneous sampling (Table 1) suggests that at least at the Homosassa and Crystal River sites an increase in abundance of wild scallops resulted from the restoration efforts. However, a genetic study designed to detect contributions from the planted scallops to subsequent generations of wild scallops failed to detect any significant contribution (Seyoum et al., 2003; Wilbur et al., 2005). Given the extreme fluctuations in scallop abundance observed from long-term fisheries landings (Fig. 2) and from the adult scallop monitoring program (Table 1), natural fluctuations as an explanation of the sudden resurgence cannot be ruled out.

A novel approach to rebuilding scallop populations has recently been developed and was applied in Pine Island Sound during November 2003 (Leverone et al., 2004; Arnold, 2008). For this effort, adult scallops were collected from Pine Island Sound and induced to spawn in a hatchery. Resultant larvae were raised to the pediveliger stage, at which time they are anticipated to set within approximately 24 hours. The larvae were then transported to the field and released into three pre-established enclosures constructed from sediment containment booms (Fig. 3). Larvae were allowed 72 hours to settle, after which the containment booms were removed and the scallops were allowed to grow to adult size and to spawn in a natural setting.

This approach is designed to emulate the caging approach, with each enclosure serving the same purpose as a set of five cages at each of the stations mentioned above. In both cases, the idea is to establish a concentration of spawning individuals and ultimately to maximize the fertilization success of the scallops that do successfully survive to spawning. However, the larval release approach

[2]Sheng, P. Physical oceanographer, Coastal Eng. Dep., Univ. Fla. Gainesville. Personal commun.

achieves that goal with considerably less cost and effort and with the scallops proceeding through their growth and development in a natural manner.

The larval release approach appears to have been successful. Recruit collectors deployed within the enclosures captured an average of 1.5 scallop recruits, whereas no recruits could be found on collectors deployed outside of the enclosures or within a control enclosure that received no larvae. Moreover, during June 2004 we found an average of 20 scallops within the footprint of the three treatment enclosures versus only three scallops within the footprint of the control enclosure.

Finally, surveys conducted in Pine Island Sound during June 2005, when offspring from the June 2004 adults would be expected to have achieved adult size themselves, revealed that scallop density in Pine Island Sound increased by two orders of magnitude relative to the previous 11 years of monitoring (Table 1). Scallop density in Pine Island Sound decreased by an order of magnitude in 2006 relative to 2005, suggesting that restoration outcomes may be short-lived and may need to be continuous to be successful.

As with the previous restoration efforts, despite apparent success we have no absolute evidence of a connection between our restoration efforts and the resultant resurgence of scallops in Pine Island Sound. Given the vagaries of population abundance characteristic of this short-lived animal, it is possible that the increase in scallop abundance observed during 2005 simply reflected natural variation. The 2003–05 effort in Pine Island Sound was designed to be low-cost so no genetic assessment was included, but we are refining and applying genetic assessment in our ongoing restoration program. Genetic assessments are a costly but necessary component of population rebuilding programs as they provide the best assurance that perceived success is a reality.

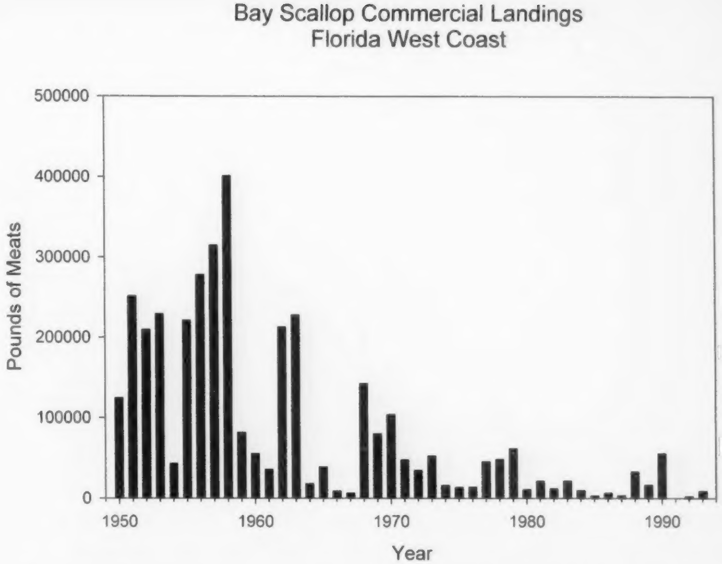


Figure 2.—Bay scallop, *Argopecten irradians*, commercial fishery landings from the west coast of Florida during 1950–93. The commercial fishery was closed by regulation beginning in 1994. Data are courtesy of the Florida FWCC Fish and Wildlife Conservation Commission's Fisheries Dependent Monitoring group.

Figure 3.—Sediment containment booms formed into enclosures for receipt of bay scallop, *Argopecten irradians*, larvae in Pine Island Sound, Fla. For the study described in the text, one of the four enclosures served as a control and received no larvae. Photo from the author's archives.

### Fishery and Harvest Regulations

Apparently beginning in the late 1920's (Murdock, 1955), an occasionally substantial commercial fishery was once active along both coasts of Florida. Most production came from Pine Island Sound and St. Joseph Bay (Table 2), but landings were recorded from several other counties including Brevard, Volusia, Flagler, and St. Johns. All four of those counties are located along the east central coast of Florida, well north of reported northernmost distribution of the species on the east coast of Florida (Waller, 1969). This fishery was sometimes substantial; in 1936 over 332,000

Table 2.—Statewide Florida commercial landings of bay scallops, *Argopecten irradians*, from 1928 through 1950. Data are from Murdock (1955) who provides additional information on the various sources of these data. * indicates missing data or no production.

| Year | Pounds of meats | Value (dollars) | Dollars/ Pound |
|---|---|---|---|
| 1928 | 14,100 | 5,000 | 0.35 |
| 1929 | * | * | * |
| 1930 | 21,867 | 2,139 | 0.10 |
| 1931 | 13,526 | 924 | 0.07 |
| 1932 | 61,965 | 6,885 | 0.11 |
| 1933 | * | * | * |
| 1934 | 74,100 | 6,596 | 0.11 |
| 1935 | * | * | * |
| 1936 | 332,100 | 32,523 | 0.10 |
| 1937 | 118,600 | 9,499 | 0.08 |
| 1938 | 137,400 | 10,593 | 0.08 |
| 1939 | 119,100 | 10,948 | 0.09 |
| 1940 | 128,400 | 17,497 | 13.6 |
| 1941 | 105,508 | * | * |
| 1942 | 42,965 | * | * |
| 1943 | 849 | * | * |
| 1944 | 21,499 | * | * |
| 1945 | 108,000 | 21,600 | 0.20 |
| 1946 | 214,366 | * | * |
| 1947 | * | * | * |
| 1948 | * | * | * |
| 1949 | 135,900 | 27,180 | 0.20 |

lbs of meats were landed and in 1951 over 250,000 lbs of meats were landed. However, the fishery was also very sporadic, and Murdock (1955) suggests that at least some of this variance was due to red tide, *Karenia brevis*, events that still severely affect bay scallop populations in Florida.

Vessels involved in this fishery were typically 15–20 ft (4.5–6 m) long, they had shallow drafts suitable for running in shallow water, and each was manned by one fisherman (Murdock, 1955). Their engines were centrally located, and a culling board was attached to the stern gunwhale. Dredges, constructed from a triangular iron frame of maximum dimensions 28 in (70 cm) wide × 24 in (60 cm) high, with a 2 2/3 in (7 cm) stretch mesh net attached to the distal end of the frame, were the harvest gear of choice. The dredges could hold about one bushel; two dredges were towed from each vessel. In Pine Island Sound, a maximum of perhaps 40 fishermen moved in and out of this fishery depending upon scallop abundance and the abundance of other harvestable species such as blue crabs, *Callinectes sapidus*. No information was provided regarding the number of fishermen engaged in the fishery in other Florida areas (Murdock, 1955).

Scallops were shucked by hand, and the women and high school girls and boys employed could shuck a bushel in less than an hour (Murdock, 1955). The resultant meats were washed to remove any shell and visceral fragments and placed in metal bins with fresh water and ice for an initial chilling. The meats absorbed some water, which increased their volumes and also improved their appearance by whitening them. The meats then were packed in 1-gallon tins which were subsequently packed on ice in barrels or boxes for shipment to local or out-of-state markets.

There were no regulations regarding this fishery (Murdock, 1955), with the predictable result that by the 1960's landings were decreasing. By the 1970's, the fishery was artisanal at best. The first substantial regulations regarding commercial or recreational bay scallop harvests in Florida were implemented in 1985, when a statewide closed season from 1 April through 30 June of each year was instituted. A recreational bag limit of five gallons of whole scallops also was put into effect and allowable dimensions for commercial harvest gear were defined.

As scallop populations continued to decline statewide, more stringent harvest regulations were instituted beginning in 1994. That year the commercial fishery was closed and commercial sale of bay scallops harvested from Florida waters was prohibited. In addition, the recreational harvest was limited to the area north of the Suwannee River and only during the period 1 July–30 Sept. of each year. In 1995 the recreational harvest season was further limited to the period 1 July–30 Aug., and the bag limit was reduced to 2 gallons of whole scallops or 1 pint of meats/person. A boat limit of 10 gallons of whole scallops (1/2 gallon of meats) was included, the prohibition on commercial sale was continued, and the use of any mechanical gear for harvest was outlawed.

In 1997 the recreational season was extended to 10 Sept. to include the Labor Day holiday, but all other regulations were left intact. Finally, in 2002, the area from the Suwannee River south to the Weeki Wachee River was reopened to harvest and the area from the mouth of St. Joseph Bay west to the Florida–Alabama line was closed to harvest due to low scallop abundance in the estuaries of that area. As of 2009, those regulations remain in effect.

As noted, considerable effort has been expended on restoring bay scallop populations in various Florida estuaries, but no definitive evidence can be offered regarding the success of those efforts. One reason for advising caution in the interpretation of the possible outcomes of those efforts relates to the changes that have occurred in harvesting regulations contemporaneous with those restoration efforts. Possibly, changes in management strategies, the restoration efforts, or a combination of the two will be adequate to maintain functional bay scallop populations in Florida coastal waters in the face of continued human population growth. The loss of bay scallops from Florida waters would be a disappointment because the species supports an enjoyable and family-oriented recreation, and that loss would signal that serious environmental problems within the seagrass community are occurring.

## Acknowledgments

Many people have contributed to our understanding of the history and ecology of bay scallops in Florida waters, including numerous citizens who contributed their memories and knowledge of scallop distribution and abundance. Specific acknowledgment goes to Alcee Taylor from Cortez, Florida, for the time he spent discussing the history of scallops and to Dr. Norm Blake and his students for establishing research baselines for bay scallops in Florida. Florida FWCC staff who have been instrumental in developing our knowledge of this important and charismatic species include Dan Marelli, Catherine Bray, Melissa Harrison, Kate Hagner, Melanie Parker, Sarah Stephenson, Steve Geiger, Janessa Cobb, Mark Gambordella, Bill Teehan, and others too numerous to mention.

## Literature Cited

Abbott, R. T. 1974. American seashells: The marine mollusca of the Atlantic and Pacific coasts of North America, second edition. Van Nostrand Reinhold Co., N.Y., 663 p.

Arnold, W. S. 2008. Application of the larval life history phase for restoration of coastal marine bivalve populations. Rev. Fish. Sci. 16:65–71.

________, N. J. Blake, M. M. Harrison, D. C. Marelli, M. L. Parker, S. C. Peters, and D. E. Sweat. 2005. Restoration of bay scallop (*Argopecten irradians* (Lamarck)) populations in Florida coastal waters: Planting techniques and the growth, mortality and reproductive development of planted scallops. J. Shellfish Res. 24:883–904.

________, D. C. Marelli, C. P Bray, and M. M. Harrison. 1998. Recruitment of bay scallops *Argopecten irradians* in Floridan Gulf of Mexico waters: scales of coherence. Mar. Ecol. Prog. Ser. 170:143–157.

Barber, B. J., and N. J. Blake. 1983. Growth and reproduction of the bay scallop, *Argopecten irradians* (Lamarck) at its southern distributional limit. J. Exp. Mar. Biol. Ecol. 66:247–256.

________ and ________ . 1985. Substrate catabolism related to reproduction in the bay scallop, *Argopecten irradians concentricus*, as determined by O/N and RQ physiological indexes. Mar. Biol. 87:13–18.

Blake, N. J. 1996. Demonstration of large-scale reintroduction of the southern bay scallop to Tampa Bay, Florida. Final Rep. Tampa Bay Natl. Est. Prog., St. Petersburg, Fla., 28 p.

________. 1998. The potential for reestablishing bay scallops to the estuaries of the west coast of Florida. Trans. 63rd No. Am. Wildl. and Natur. Resour. Conf., p. 184–189.

________ and M. A. Moyer 1991. The calico scallop, *Argopecten gibbus*, fishery of Cape Canaveral, Florida. *In* S.E. Shumway (Editor), Scallops: biology, ecology and aquaculture, p. 899–911. Develop. Aquacult. Fish. Sci., Vol. 21, Elsevier, N.Y..

Castagna, M. 1975. Culture of the bay scallop, *Argopecten irradians*, in Virginia. Mar. Fish. Rev. 37(1):19–24.

Coleman, F. C., C. C. Koenig, and W. F. Herrnkind. 1994. Survey of Florida inshore shrimp trawler by-catch. Second annual report, Fla. Dept. Nat. Resour., Fla. Mar. Res. Inst., DNR contract #C-7779, 56 p.

Hanski, I. 1991. Single-species metapopulation dynamics: concepts, models and observations. Biol. J. Linn. Soc. 42:17–38.

Leverone, J. R., W. S. Arnold, S. P. Geiger, and J. Greenawalt. 2004. Restoration of bay scallop populations in Pine Island Sound: Competent larval release strategy. Final report to the Charlotte Harbor Natl. Est. Prog. Mote Mar. Lab. Tech. Rep. 974, 13 p.

Levins, R. 1969. Some demographic and genetic consequences of environmental heterogeneity for biological control. Bull. Entomol. Soc. Am. 15:237–240.

Levitan, D. R. 1995. The ecology of fertilization in free-spawning invertebrates. *In* L. McEdward (Editor), Ecology of marine invertebrate larvae, p. 123–156. CRC Press, Boca Raton, Fla.

Lewis, R. R., M. J. Durako, M. D. Moffler, and R. C. Phillips. 1985. Seagrass meadows in Tampa Bay-a review. *In* S. A. F. Treat, J. L. Simon, R. R. Lewis III, and R. L. Whitman, Jr. (Editors), Proceedings Tampa Bay Area Scientific Information Symposium, p. 210–246. Fla. Sea Grant Coll. Rep. 65.

Lu, Y., and N. J. Blake. 1997. The culture of the southern bay scallop in Tampa Bay, an urban Florida estuary. Aqua. Intern. 5:439–450.

Marelli, D. C., and W. S. Arnold. 2001. Shell morphologies of bay scallops, *Argopecten irradians*, from extant and prehistoric populations from the Florida Gulf coast: Implications for the biology of past and present metapopulations. J. Archaeol. Sci. 28:577–586.

________ , M. K. Krause, W. S. Arnold, and W. G. Lyons. 1997a. Systematic relationships among Florida populations of *Argopecten irradians* (Lamarck, 1819) (Bivalvia: Pectinidae). The Nautilus 110:31–41.

________ , W. G. Lyons, W. S. Arnold, and M. K. Krause. 1997b. Subspecific status of *Argopecten irradians concentricus* (Say, 1822) and of the bay scallops of Florida. The Nautilus 110:42–44.

Mikell, G. A. 1992. 80K5: A coastal Weeden Island village in northwest Florida. The Fla. Anthropol. 45:195–220.

________ . 1994. 8WL38, A protohistoric village site on Choctawhatchee Bay. The Fla. Anthropol. 47:233–267.

Moyer, M. A., and N. J. Blake. 1986. Fluctuations in calico scallop production (*Argopecten gibbus*). Proc. 11th Annu. Trop. Subtropical Fish. Conf. Am., p. 45–58.

Murdock, J. F. 1955. Investigation of the Lee County bay scallop fishery. Rep. 55-13, The Mar. Lab., Univ. Miami, Fla., 10 p.

Seyoum, S., T. M. Bert, A. Wilbur, C. Crawford, and W. S. Arnold. 2003. Development, assessment, and application of a mitochondrial DNA genetic tag for the bay scallop, *Argopecten irradians*. J. Shellfish Res. 22:111–117.

Thayer, G. W., and H. H. Stuart. 1974. The bay scallop makes its bed of seagrass. Mar. Fish. Rev. 36(7):27–30.

Thomas, P. L., and L. J. Campbell. 1993. Eglin Air Force Base historic preservation plan, Technical synthesis of cultural resources investigations at Eglin, Santa Rosa, Okaloosa and Walton Counties, Florida. New World Res., Inc., Rep. Invest. 192. Chap. 8, Prehistoric Interpret., p. 489–637.

Wakida-Kusunoki, A. T. 2009. The bay scallop, *Argopecten irradians amplicostatus*, in northeastern Mexico. Mar. Fish. Rev. 71(3):17–19.

Waller, T. R. 1969. The evolution of the *Argopecten gibbus* stock (Mollusca: Bivalvia), with emphasis on the tertiary and quaternary species of eastern North America. The Paleontological Society Memoir 3(43):1–125.

Wilbur, A. E., S. Seyoum, T. M. Bert, and W. S. Arnold. 2005. A genetic assessment of bay scallop (*Argopecten irradians*) restoration efforts in Florida's Gulf of Mexico coastal waters (USA). Cons. Gen. 6:111–122.

# Bay Scallops, *Argopecten irradians*, in the Northwestern Gulf of Mexico (Alabama, Mississippi, Louisiana, and Texas)

KIM WITHERS and MATT HUBNER

## Introduction

Two subspecies of bay scallops inhabit the northwestern Gulf of Mexico coast: *Argopecten irradians concentricus* on the west coast of Florida to the Chandeleur Islands, Lousiana, and *A. i. amplicostatus* from Galveston Bay, Texas, south to northern Mexico. Abundance of bay scallops in the northwestern Gulf is typically much lower than on the west coast of Florida and the Atlantic coast. Alabama, Mississippi, and Louisiana have not reported a commercial scallop catch since harvest statistics began being published in 1950.[1] Texas reported its only commercial catches (since 1895) in 1984 and 1985 (Culbertson et al., 2004). The landings for both years combined were 2.4 metric tons (t) with a market value of $2,746.00. In the same years, 13,437 t of bay scallops with a total value of $35,842.00 were landed in Florida.[1] Texas is the only state in the northwestern Gulf that regulates recreational harvesting of scallops (TPWD, 2002, 2006). Scallops can only be harvested from waters approved by the Texas Department of Health. They can be taken year-round by hand, using dip nets, rakes, or dredging and there are no size or bag limits.

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*ABSTRACT—There is no evidence that a commercial bay scallop fishery exists anywhere in the northwestern Gulf of Mexico. No data concerning scallop abundance or distribution was found for Alabama, Mississippi, and Louisiana. Texas is the only state west of Florida where bay scallop populations have been documented. These records come from a variety of literature sources and the fisheries-independent data collected by Texas Parks and Wildlife Department (1982–2005). Although common in the diet of prehistoric peoples living on the Texas coast, recent (last ~50 years) bay scallop population densities tend to be low and exhibit "boom–bust" cycles of about 10–15 years. The Laguna Madre, is the only place on the Texas coast where scallops are relatively abundant; this is likely due to extensive seagrasses cover (>70%) and salinities that typically exceed 35 psu. The lack of bay scallop fishery development in the northwestern Gulf of Mexico is probably due to variable but generally low densities of the species combined with a limited amount of suitable (i.e. seagrass) habitat.*

Since there is no fishery on the northwestern Gulf of Mexico, this paper will focus on what is known about past and present bay scallop distribution and abundance in the northwestern Gulf (primarily Texas, Fig. 1) and the reasons why a commercial fishery is unlikely to develop.

## Prehistoric Scallop Usage

Shell middens composed primarily of eastern oyster, *Crassostrea virginica*, or rangia, *Rangia cuneata* and/or *R. flexuosus*, shells are common along much of the northwestern Gulf of Mexico coast. The predominant species depends on whether they were deposited in low salinity areas near river deltas and bay heads (rangia), or in areas of higher salinity closer to the Gulf along bay margins and barrier islands (oysters). Texas shell middens usually represent sites of repeated seasonal occupation (Ricklis, 1995), but on the Louisiana Chenier plain, middens can be difficult to separate from natural accumulations of shell (Henderson et al., 2002).

Scallops do not appear in middens from Louisiana (e.g. Poverty Point Site; Gagliano and Saucier, 1963) but they are a common component of middens in northwestern Florida (Russo and Quitmyer, 1996) and Texas (Table 1). We could find no record of marine/estuarine shell middens or bay scallop artifacts in either Mississippi or Alabama. Rangia or freshwater forms dominate the few middens in Louisiana that have been studied (Henderson et al., 2002), suggesting that estuarine salinities may have been too low outside of Texas and Florida to support large prehistoric scallop populations.

Bay scallops are one of five species of marine/estuarine mollusks that were exploited by prehistoric inhabitants of the Texas coastline. Their shells are often co-dominant with oyster shells (Ricklis, 1995), but they are not usually associated with middens dominated by rangia shells. Bay scallops are infrequently found in middens on the upper Texas coast and are much more abundant from Matagorda Bay southward (Steele, 1987; Table 1). The majority of bay scallop shells found in archeological sites are unmodified, even articulated, and in large enough quantities to suggest they were a significant and integral food source (Steele, 1987; Ricklis, 1996). Scallops were apparently not used for tools or ornaments since possibly modified shells were only found at two sites (Steele, 1987).

Bay scallops are most abundant in middens that date to the early Archaic period (~7500–4500 YBP). At that

[1]Landings statistics have been published by the National Marine Fisheries Service, NOAA, in various issues of the Current Fisheries Statistics series

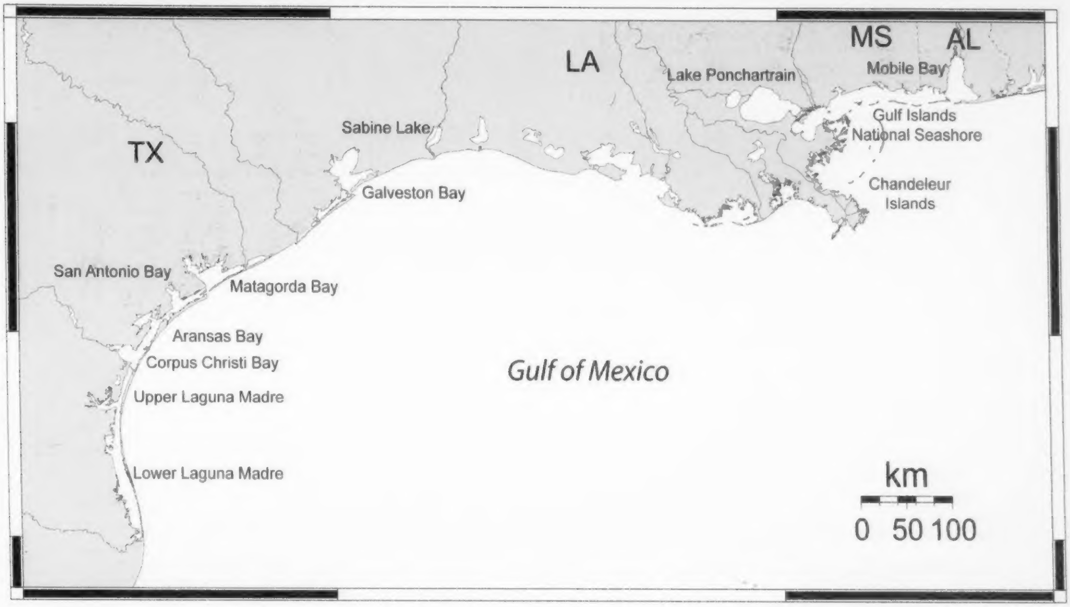


Figure 1.—Map of the Gulf States west of Florida, showing bay systems and other locations mentioned in the text.

**Table 1.—Occurrences of bay scallops in archeological contexts on the Texas Gulf Coast.**

| Bay | Site Name or Number | Date | Remarks | Source |
|---|---|---|---|---|
| Galveston Bay | Multiple | Not available | Bay scallop present in middens, but not abundant | Steele, 1987 |
| Lavaca Bay | Multiple | Not available | Bay scallop present in middens | Steele, 1987 |
| Matagorda Bay | Multiple | Not available | Bay scallop absent from middens | Steele, 1987 |
| Copano Bay | 41AS5 | 2740–2500 YBP[1] | Bay scallops present in midden | Ricklis and Albert, 2005 |
| | 41AS15 | Archaic–prehistoric | Bay scallops were ~2% of 183 kg of shell | Prewitt and Paine, 1987 |
| | 41AS3 | 2764–2727 YBP[1] | Bay scallops common | Ricklis, 1995 |
| Aransas Bay | Johnson Site | Archaic | Bay scallops common | Shafer and Bond, 1985; Campbell, 1947 |
| Nueces Bay | 41SP15 | 5257–4875 YBP[1] | Dense oyster & bay scallop | Ricklis and Cox, 1991 |
| | 41SP153 Unit 1 | 7509–9857 YBP[1] | Dense oyster & scallop | Ricklis, 1993 |
| | 41SP153 Area 2 | 5888–4568 YBP[1] | Dense oyster & bay scallop | Ricklis, 1993 |
| | 41SP156 | 5592–4614 YBP[1] | Dense oyster & bay scallop | Ricklis, 1993 |
| | 41SP177 | 3156–2873 YBP[1] | Moderate oyster, some bay scallop | Ricklis, 1993 |
| Corpus Christi Bay | 41SP120 South Block | 1161–730 YBP[1] | Dense mixed shell midden (oyster, bay scallop, quahog, whelk, others) | Ricklis and Cox, 1991 |
| | 41SP120 North Block | 1338–741 YBP[1] | Dense mixed shell midden (oyster, bay scallop, whelk, quahog, others) | Ricklis, 1993 |
| | 41SP11 | 626–533 YBP[1] | Scattered shell, including bay scallop | Ricklis, 2006 |
| | 41NU65 | Archaic–prehistoric | 2 bay scallop shells recovered | Steele and Mokry, 1985 |
| | 41NU101 | Archaic–prehistoric | 2 bay scallop shells recovered | Steele and Mokry, 1985 |
| | 41SP43/120 | Archaic | 2,000 fragments, bay scallop 2nd to oyster in abundance | Ricklis, 1987 |
| Laguna Madre | Multiple sites | Not available | Bay scallop present | Steele, 1987 |
| Baffin Bay | 41KL13 | Archaic–prehistoric | Bay scallop and other shell present on surface | Hester, 1971 |
| | 41KL71 | 4552±60 YBP[2] | Midden contained oyster, whelk, tulip shell, and bay scallop | Smith, 1986 |
| | 41KL37 | Archaic | Whelk, oyster, bay scallop, and tulip shell scatter | Smith, 1986 |

[1] These dates represent age before present (YBP) calibrated 1-sigma age ranges (Ricklis, 1995).
[2] This date is an uncorrected radiocarbon date on charcoal from the site (Smith, 1986).

time, barrier islands had not yet formed off the Texas coast, and estuaries were open with unrestricted exchange with the Gulf of Mexico. Shellfish were a seasonally (fall, winter, early spring) important source of both calories and protein, and exploitation was fairly intense. At the Holmes Site on Corpus Christi Bay, scallop shells dominated the deposit and were abundant enough to have yielded an estimated 15,750 g of meat (Ricklis, 1996).

After the barrier islands formed (~4000 YBP), fish and mammal remains dominate midden assemblages. Shellfish

Table 2.—Occurrences and estimated abundance of bay scallops in bays along the Texas Gulf Coast compiled from various published and unpublished sources.

| Year | Bay Scallop Occurrence/Estimated Abundance by Bay | | | | | | | | | | | | Sources |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | SL | GB | MB | ES | SA | AB | CB | RB | CC | NB | ULM | LLM | |
| 1894 | | D | | | | | | | P | | | | Evermann and Kendall, 1894 |
| 1940 | | | | | | C | | | | | | | Ladd, 1951 |
| 1951–58 | | | | R | | VA | | R | | | | VA | Parker, 1959 |
| 1959–60 | | R | | | | | | | | | | | Shidler, 1960 |
| 1967 | | | | | | | | A[1] | | | | | Zimmerman and Chaney, 1969 |
| 1968 | | | | | | | | R | | | | | Zimmerman and Chaney, 1969 |
| 1971–73 | | | | | 0 | | | | | | 0 | | Harper, 1973a, 1973b; Hildebrand and King, 1973 |
| 1973–74 | | | | | | P | P | | 0 | | | | Hildebrand and King, 1974; Holland et al., 1974 |
| 1974–75 | | | | | | | | R–C | 0 | | 0 | | Hildebrand and King, 1975; Rickner, 1975 |
| 1975–76 | | | | | | | D | | 0 | | VA | | Hildebrand and King, 1976; Calnan, 1980 |
| 1976–77 | 0 | D | D | D | D | R | D | D | D | 0 | 0–VA | 0 | Hildebrand and King, 1977; Circé, 1979; White et al., 1985, 1986a, 1986b, 1987, 1989a, 1989b |
| 1977–78 | | | | | | | | | 0 | | R–C | P | Hildebrand and King, 1979; Rickner, 1979; Williamson, 1980; Brock, 1983 |
| 1980 | | | | | | | | | | | D | | Wilhite et al., 1982 |
| 1981–82 | | | | | | | | | R | | R | | Powell et al., 1982; Castiglione, 1983 |
| 1984 | | | | | | | | | | | D | D | Smith, 1985 |
| 1986–87 | | | | | | | | | | F | C | | Chaney, 1988; Drumright, 1989 |
| 1989–90 | | | | | | | | | | 0 | 0 | 0 | Ruth, 1991; Hicks, 1993; Hicks et al., 1998 |
| 1992–93 | | | | | | | | | 0 | | 0 | | Montagna, 1993; Martin, 1994; Montagna and Martin, 1994 |
| 2001–02 | | | | | | | | R | | | 0 | | Davidson. 2002; Pearce, 2003 |
| 2004 | | | | | | | | | | | A | | Withers, K, pers. observ. |
| 2005 | | | | | | | | | | | C–A | C | Withers, K, pers. observ.; Hicks, D. W., Univ. Texas-Brownsville, pers. commun. |
| 2006 | | | | | | | | | | | R | | Hubner, 2007 |

[1] Scallops were freshly dead with tissues still attached.

Bay abbreviations:
SL = Sabine Lake
GB = Galveston Bay system, including Trinity Bay
MB = Matagorda Bay system, including Lavaca Bay
ES = Espiritu Santo Bay
SA = San Antonio Bay system, including Hynes and Mesquite bays
AB = Aransas Bay, including St. Charles Bay
CB = Copano Bay; RB = Redfish Bay
CC = Corpus Christi Bay, including Oso Bay
NB = Nueces Bay
ULM = Upper Laguna Madre
LLM = Lower Laguna Madre, including South Bay

Abundance rankings use the author's terminology or were determined as follows:
D = dead only
P = present in a species checklist, but no abundance data provided
0 = none collected
R = rare: less than 5% of total collection.
F = few: 6–10% of collection
C = common: 15–40% of collection or 40–50% of sites
A = abundant: 41–60% of collection or 51–75% of sites
VA = very abundant: numerically dominant and present in most sites sampled

remains are much less abundant in middens deposited after ~3000 YBP (late Archaic). Changing salinities in the newly enclosed bays, concomitant changes in shellfish species composition and abundance, technological advancements, and increasing human populations probably all contributed to reduced importance of shellfish exploitation in the estuaries and greater reliance on fishing and hunting. However, shellfish remained a part of the diet of the native peoples up through historic times. Cabeza de Vaca (early 1500's) and De Bellisle (early 1700's), two early explorers of the Texas Coast, observed opportunistic and deliberate harvest of shellfish, including scallops (Newcomb, 1961).

## Recent Abundance and Distribution

Our review of the literature turned up no mentions of living or dead bay scallops in Louisiana, Mississippi, or Alabama. Queries to fishing guides in the Chandeleur Islands area of Louisiana yielded sightings of bay scallop shells, but no reports of live scallops. In Texas, two sources of data for scallop abundance and distribution are available for evaluation: a variety of published and unpublished literature and reports (1894–2006) and quantitative, coastwide fisheries independent monitoring data collected by the Texas Parks and Wildlife Department (TPWD) for 1982–2005.

### Literature Records

An exhaustive review of the literature for Texas turned up 40 sources with references to bay scallop distribution and abundance (Table 2). These ranged from reports or counts of dead shell in samples (Powell et al., 1982; Smith, 1985; White et al., 1985–89), and mentions in species checklists (Evermann and Kendall, 1894; Holland et al., 1974), to more quantitative studies that provide a qualitative estimate of abundance (Ladd, 1951), data that allows a reasonable estimation of local abundance, frequency, or both (Hildebrand and King, 1973–79) or samples were taken such that scallops could or should have been collected, but were not (Calnan, 1980; White et al., 1985–89).

Most records represent collections at only one or a few sites within a single bay system. The only comprehensive studies were those by the Bureau of Economic Geology in the mid to late 1970's. Composition and abundance of benthic fauna were included in comprehensive studies of the bottoms on "submerged lands" of the bays and inner shelf of the Texas coast (White et al., 1985–89). Studies focused on shoalgrass, *Halodule wrightii,* beds

(Corpus Christi Bay, Laguna Madre), and turtlegrass, *Thalassia testudinum*, beds (Redfish Bay) yielded the majority of scallop records.

The upper Laguna Madre has been studied more than the other bays and has a more complete record of when scallops have been present. During 1976–77 when all bays were sampled, live scallops were only found in Aransas Bay and upper Laguna Madre. Scallops were abundant in areas of Aransas Bay and lower Laguna Madre in the 1950's, and in parts of upper Laguna Madre in 1975–77 and 2004–05.

### TPWD Independent Fisheries Data

Since 1982, nekton have been sampled in each Texas bay system using bag seines and trawls. Both of these gears will also capture bay scallops and, when collected, their numbers and sizes have been recorded. Bay systems are divided into grids, grids are stratified by depth (trawls vs. bag seines), and 20 grids are randomly chosen from each stratum prior to each sampling event. A sampling station within the grid is randomly chosen. No grid can be sampled more than once per month with the same gear. We obtained bag seine and trawl data for 1982–2005 from the Texas Parks and Wildlife's Coastal Fisheries Division, as described in Martinez-Andrade et al. (2005).

Very few scallops were collected in bag seines in any bay (Table 3). Scallops were not collected from Sabine Lake or the Galveston Bay system in either bag seines or trawls. The majority of scallops were collected in trawls in the upper Laguna Madre (Table 4). Trawls outside the Laguna Madre yielded few scallops and from 1991–98 no scallops were collected in trawls from any bay except lower Laguna Madre. Scallops were most abundant in 1987–88 and 2004; more than 95% of these were trawled from the upper Laguna Madre.

Scallops collected in bag seines were largest (mean length 43.4 mm) in Corpus Christi Bay and smallest (mean length 27.9 mm) in upper Laguna Madre (Table 5). Scallops trawled from Aransas and San Antonio bay systems were generally larger than those from other bay systems (Table 6). Average length (San Antonio Bay = 39.9 mm; Aransas Bay = 43.3 mm) of scallops in these two systems was larger than on the rest of the coast and was slightly larger than seined scallops in the same bays. Average shell lengths of scallops trawled from Corpus Christi Bay and the Laguna Madre were smaller than the average of seined specimens.

During 2004, shell length, width, and dry weight as well as scallop body dry weight were determined on a sample

**Table 3.—Total numbers of bay scallops collected in bag seines 1982–2005. Data provided by Texas Parks and Wildlife Department.**

| Year | Matagorda Bay | San Antonio Bay | Aransas Bay | Corpus Christi Bay | Upper Laguna Madre | Lower Laguna Madre |
|---|---|---|---|---|---|---|
| 1982 | | | | | | |
| 1983 | | | | | | |
| 1984 | | | | | | |
| 1985 | | | | 3 | | |
| 1986 | | | | | | |
| 1987 | | | | | | |
| 1988 | | | | 2 | 8 | |
| 1989 | | 4 | 1 | 1 | | |
| 1990 | | 4 | | 3 | 1 | |
| 1991 | | 1 | | 2 | | 3 |
| 1992 | | | | | | |
| 1993 | | | | 1 | | |
| 1994 | | | | | | |
| 1995 | | 1 | | 3 | | |
| 1996 | 1 | 5 | 2 | 5 | | |
| 1997 | 1 | 1 | 2 | | | |
| 1998 | | | | | 1 | |
| 1999 | | | | | | |
| 2000 | | | | 1 | | 2 |
| 2001 | | | 1 | | | |
| 2002 | | | | | | |
| 2003 | | | | | 1 | |
| 2004 | | | | | 6 | |
| 2005 | | | | | 1 | |
| Total | 2 | 16 | 6 | 21 | 18 | 5 |

**Table 4.—Total numbers of scallops collected in trawls 1982–2005. Data provided by Texas Parks and Wildlife Department.**

| Year | Matagorda Bay | San Antonio Bay | Aransas Bay | Corpus Christi Bay | Upper Laguna Madre | Lower Laguna Madre |
|---|---|---|---|---|---|---|
| 1982 | | | | | 10 | |
| 1983 | | | | | 25 | |
| 1984 | | | | | 12 | |
| 1985 | | | | | 9 | |
| 1986 | | | | | 10 | |
| 1987 | | | | | 385 | 9 |
| 1988 | | 3 | | 7 | 395 | 7 |
| 1989 | 1 | 6 | 4 | | 2 | 8 |
| 1990 | | 1 | 1 | | 1 | 8 |
| 1991 | | | | | | 2 |
| 1992 | | | | | | 33 |
| 1993 | | | | | | 1 |
| 1994 | | | | | | 1 |
| 1995 | | | | | | 10 |
| 1996 | | | | | | 1 |
| 1997 | | 1 | | 2 | | |
| 1998 | | | 1 | | 4 | 1 |
| 1999 | | | | | 1 | 9 |
| 2000 | | | | | 1 | 58 |
| 2001 | 5 | | | | | 5 |
| 2002 | | | 1 | | | 2 |
| 2003 | | | | | 26 | 3 |
| 2004 | | | | | 938 | 16 |
| 2005 | | | | | 3 | 1 |
| Total | 6 | 11 | 7 | 9 | 1,822 | 175 |

of 10 bay scallops collected from Bird Island Basin in upper Laguna Madre.[2]

[2]Hubner, M., and K. Withers. Texas A&M University-Corpus Christi, 6300 Ocean Dr., Unit 5866, Corpus Christi, TX. Unpubl. data on file at the Center for Coastal Studies.

These scallops were collected during November from shoalgrass in water about 1.25 m deep. Average shell length was 53.9 mm (SD=7.2), average width was 55.2 mm (SD=7.7), and average dry weight was 23.5 g (SD=6.1). Average length of this collection was nearly double the average length of scallops in TPWD trawls during the same year. Average body dry weight was 23.5 g (SD=6.1).

Based on TPWD trawl data, scallop distribution and abundance on the Texas coast appears linked to salinity and fluctuations in salinity. Virtually all scallops were collected from waters of at least 20 psu (Fig. 2). The vast majority of scallops were collected in the hypersaline Laguna Madre (Fig. 3), especially the upper lagoon, which tends to exhibit higher salinities than the lower lagoon. When all data from coastal bays were analyzed using Spearman's rho there was a significant positive correlation between salinity and scallop abundance (correlation coefficient = 0.073; p = 0.0001; $n$ = 22,998). However, the same analysis using data only from Laguna Madre yielded a negative correlation (correlation coefficient = -0.035; p = 0.009; $n$ = 5,682). Boom years in the upper Laguna Madre generally followed years when mean annual salinity dropped to around 30 psu (Fig. 4, top). During the 1990's, a persistent brown tide in the upper Laguna Madre may have prevented a boom year following the 1992–93 salinity declines or salinities may have declined below the threshold for recruitment. In the lower Laguna Madre, scallop abundance is low but the population appears to be more consistent than in the upper lagoon (Fig. 4, bottom). "Boom" abundances (e.g. 1992, 2000) are less than 10% of boom abundances in the upper lagoon, and the pattern of increasing abundance following declining salinity is not clear.

**Table 5.—Average length (mm) of bay scallops collected in bag seines 1982–2005 with standard deviation in parenthesis (when more than 1 bay scallop was collected or measured). Data provided by Texas Parks and Wildlife Department. Asterisk (*) indicates that scallops were collected but not measured.**

| Year | Matagorda Bay | San Antonio Bay | Aransas Bay | Corpus Christi Bay | Upper Laguna Madre | Lower Laguna Madre |
|---|---|---|---|---|---|---|
| 1982 | | | | | | |
| 1983 | | | | | | |
| 1984 | | | | | | |
| 1985 | | | | * | | |
| 1986 | | | | | | |
| 1987 | | | | | | |
| 1988 | | | | 46.0 (1.4) | 31.9 (9.3) | |
| 1989 | | 43.3 (16.9) | 50.0 | 35.0 | | |
| 1990 | | 47.8 (22.6) | | 46.7 (9.1) | 36.0 | |
| 1991 | | 14.0 | | 57.5 (0.7) | | 34.8 (2.5) |
| 1992 | | | | | | |
| 1993 | | | | 35.0 | | |
| 1994 | | | | | | |
| 1995 | | 11.0 | | 42.5 (12.0) | | |
| 1996 | 26.0 | 38.5 (12.2) | 29.0 | 40.8 (21.4) | | |
| 1997 | 39.0 | 7.0 | 40.5 | | | |
| 1998 | | | | | 38.0 | |
| 1999 | | | | | | |
| 2000 | | | | 32.0 | | 51.0 (9.9) |
| 2001 | | | 38.0 | | | |
| 2002 | | | | | | |
| 2003 | | | | | 17 | |
| 2004 | | | | | 23.8 (8.4) | |
| 2005 | | | | | 21 | |
| Overall | 32.5 (9.2) | 35.9 (19.5) | 39.4 (8.6) | 43.4 (13.4) | 27.9 (9.3) | 42.9 (11.1) |

**Table 6.—Average length (mm) of bay scallops collected in trawls 1982–2005 with standard deviation in parentheses (when more than 1 bay scallop was collected or measured). Data provided by Texas Parks and Wildlife Department. Asterisk (*) indicates that scallops were collected but not measured.**

| Year | Matagorda Bay | San Antonio Bay | Aransas Bay | Corpus Christi Bay | Upper Laguna Madre | Lower Laguna Madre |
|---|---|---|---|---|---|---|
| 1982 | | | | | * | |
| 1983 | | | | | 22.4 (11.2) | |
| 1984 | | | | | 20.2 (1.0) | |
| 1985 | | | | | 21.3 (15.9) | |
| 1986 | | | | | 19.0 (8.8) | |
| 1987 | | | | | 25.9 (17.6) | 37.1 (16.8) |
| 1988 | | 32.3 | | 30.2 (6.5) | 29.0 (13.4) | 23.1 (3.5) |
| 1989 | 8.0 | 44.0 (1.4) | 47.5 (10.2) | | 25.5 (14.8) | 32.2 (26.8) |
| 1990 | | 57.0 | 40.0 | | 26 | 18.3 (6.3) |
| 1991 | | | | | | 18.0 |
| 1992 | | | | | | 23.3 (6.3) |
| 1993 | | | | | | 15.0 |
| 1994 | | | | | | 26.0 |
| 1995 | | | | | | 18.1 (6.6) |
| 1996 | | | | | | 29.0 |
| 1997 | | 22.0 | | 29.5 (2.1) | | |
| 1998 | | | 28.0 | | 18.5 | 35.0 |
| 1999 | | | | | 27.0 | 22.5 (10.4) |
| 2000 | | | | | 10.0 | 21.2 (0.22) |
| 2001 | * | | | | | 23.3 (13.1) |
| 2002 | | | 45.0 | | | 39.0 (21.2) |
| 2003 | | | | | 20.8 (9.9) | 23.3 (2.5) |
| 2004 | | | | | 18.4 (13.4) | 25.7 (10.1) |
| 2005 | | | | | 14.7 | 25.0 |
| Overall | | 39.9 (13.3) | 43.3 (10.3) | 29.9 (4.7) | 23.5 (14.1) | 25.5 (13.3) |

## Discussion

We were unable to find any records of abundance or distribution of scallops in the northwestern Gulf of Mexico outside of Texas. Fisheries-independent trawl/bag seine data and other records from Texas show that scallops appear to "boom" from Aransas Bay south at intervals of about 10–15 years (i.e. 1950's, Aransas Bay; 1967, Redfish Bay; 1976–78, 1987–1988, and 2004, upper Laguna Madre). In lower Laguna Madre, scallop populations have peri-

odically boomed (i.e. 1950's) but they may be present in low numbers more consistently than in other bays. The only year between 1987–2005 that no scallops were trawled from the lower Laguna Madre was 1997. Recruitment limitations may be responsible for "boom–bust" cycles of abundance in bay scallops (Peterson and Summerson, 1992). A recruitment study in the upper Laguna Madre during 2005–06, the year after a boom, yielded no scallop spat from 28 stations and only three adults (Hubner, 2007) suggesting that this is case in the upper Laguna Madre.

The lack of bay scallop fishery development in the northwestern Gulf of Mexico is doubtless due to variable but generally low densities of the species combined with a limited amount of suitable (i.e. seagrass) habitat. Bay scallop distribution is closely tied to seagrass distribution (Gutsell, 1930; Marshall, 1947; Eckman, 1987; Ambrose and Irlandi, 1992) and the majority of seagrasses in the northwestern Gulf are found in Texas (Table 7). Seagrass cover in Texas is inversely related to freshwater inflow and increases from north to south. The majority of Texas seagrasses (~79%) are found in the semi-arid and hypersaline Laguna Madre, with over 75,000 ha (Pulich, 1999) and greater than 70% overall coverage (Onuf, 1995). Shoalgrass is the dominant species but turtlegrass, manatee grass, *Cymodocea filiforme*, and small amounts of clover grass, *Halophila engelmannii*, and widgeon grass, *Ruppia maritima*, are also found in the system. Seagrasses fringe the shorelines of other bays (e.g. Corpus Christi Bay, Aransas Bay). Galveston Bay was the only other bay on the Texas coast where seagrasses had been fairly extensive, but by 1989 very little remained (Pulich, 1999). Recent reintroduction of seagrasses into the bay may reverse this trend.

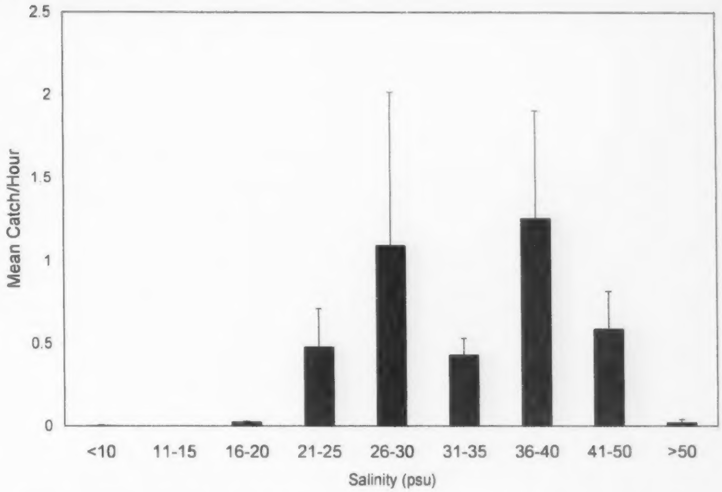


Fig. 2.—Mean abundance and standard deviation of bay scallops in Texas by salinity. Trawl and salinity data from Texas Parks and Wildlife fishery independent monitoring program, 1982–2005.

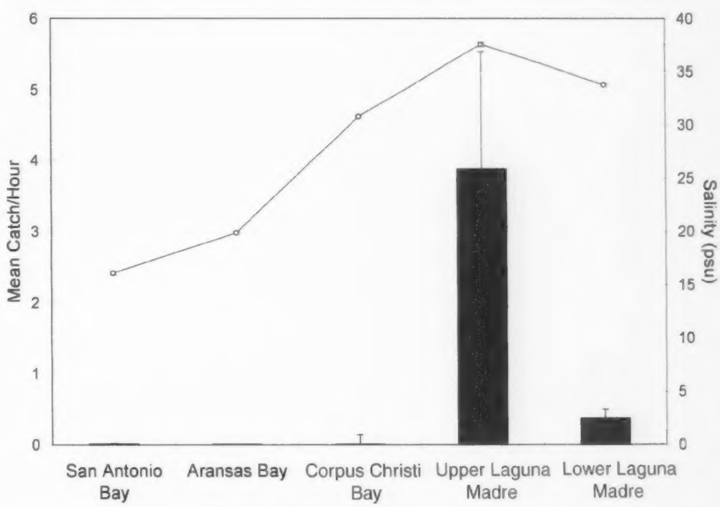


Figure 3.—Mean abundance and standard deviation of bay scallops in central and southern bay systems with overall mean salinity of each bay (line). Trawl and salinity data from Texas Parks and Wildlife fishery independent monitoring program, 1982–2005.

Submerged aquatic vegetation is found in the bays and sounds of the northern Gulf (e.g. Mobile Bay, Mississippi Sound, Lake Ponchartrain), but is often dominated by freshwater species such as wild celery, *Valisnera*, and widgeon grass. Never widespread, where shoalgrass is currently present in Alabama, coverage is much reduced from historic levels (Barry Vittor and Associates, Inc., 2005). Small amounts of seagrasses (primarily shoalgrass and manatee grass) are found on the northern sides of barrier islands in Mississippi (Handley, 1995). Losses were estimated at more than 66% from 1956 to 1992.

In Louisiana, seagrasses have been completely lost in the Mississippi Delta, behind the south coast barrier islands, and in the coastal lakes. Chandeleur Sound, an area that is mostly unaffected by human impacts, is the only part of Louisiana where seagrasses are still present. The lack of seagrasses over

Table 7.—Seagrass cover in the northwestern Gulf of Mexico.

| State | Year | Area (ha) | Trends | Source |
|---|---|---|---|---|
| Alabama (Mobile Bay area)[1] | 2002 | 349 | ↓ 55–88% | Barry Vittor and Associates, Inc., 2005 |
| Mississippi (Gulf Islands National Seashore) | 1992 | 140 | ↓ 66% | Handley, 1995 |
| Lousiana (Chandeleur Islands) | 1989 | 5,657 | ↓ 12% | Handley, 1995 |
| Texas (entire coast) | 1994 | ~94,409 | | Pulich, 1999 |
| Galveston Bay system | | 113 | ↓ 90+% | |
| Matagorda Bay system | | 1,551 | Unknown | |
| San Antonio Bay system | | 4,293 | Fluctuates | |
| Aransas Bay system | | 3,240 | Unknown | |
| Corpus Christi Bay system (including Redfish Bay) | | 9,963 | Stable | |
| Laguna Madre system | | 75,409 | Slight decrease | |

[1] Includes all submerged aquatic vegetation; seagrasses were not separable, but they represented only a small percentage of all submerged vegetation mapped in the study (Barry Vittor and Associates, Inc. 2005)

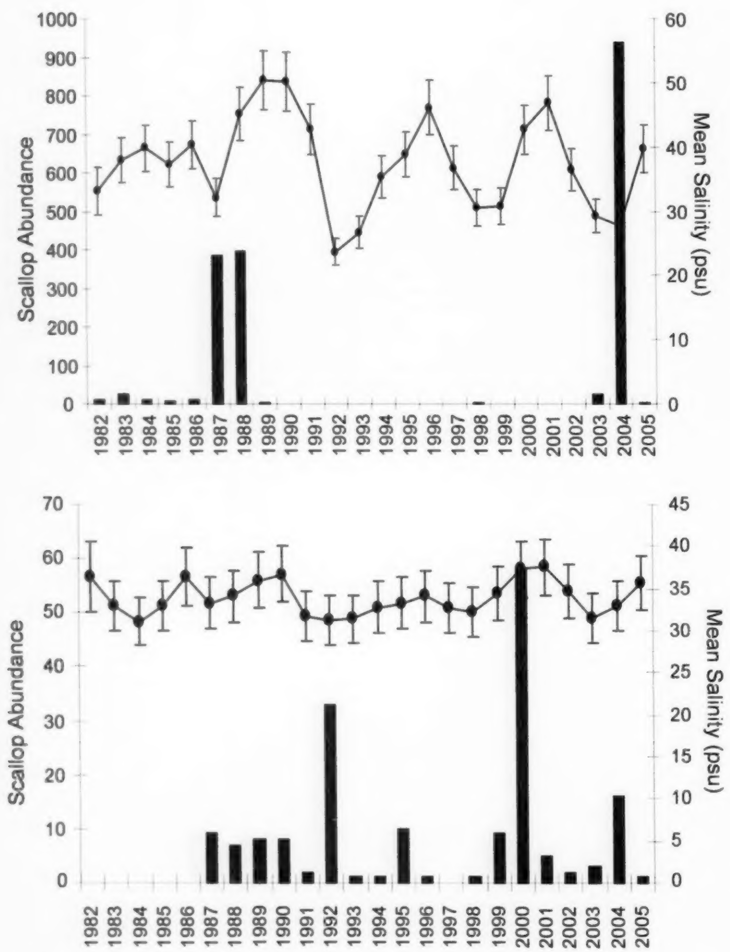


Figure 4.—Overall abundance of bay scallops and mean annual salinity (line) in upper Laguna Madre (top) and lower Laguna Madre (bottom). Trawl and salinity data from Texas Parks and Wildlife fishery independent monitoring program, 1982–2005.

much of the northwestern Gulf, due largely to low average salinities and high turbidity (Handley, 1995), accounts for the lack of scallop records north of Matagorda Bay, Texas.

Another component to add to the complexity of bay scallop abundance patterns in Texas was the persistent and continuous brown-tide bloom in the upper Laguna Madre from 1990–98 (Montagna et al., 1993). The freeze of 1989 and subsequent brown tide have been anecdotally blamed for the absence of bay scallops in the upper Laguna Madre throughout much of the 1990's. Brown tides have plagued New England estuarine complexes since the 1970's and have been implicated in decline of bivalve populations, including the bay scallop (Bricelj and Lonsdale, 1997). The algal blooms affect scallop populations by: 1) reducing the efficiency of filter feeding in adults (Cosper et al., 1989); 2) limiting food sources for larval scallops (Gallager et al., 1989); 3) gamete resorption in reproductive adults (Tracey, 1988); and 4) habitat loss due to increased turbidities (Tettelbach and Wenczel, 1993). Light attenuation from the Texas brown tide had caused a loss of ~940 ha of seagrass cover in the upper Laguna Madre by 1995 (Onuf, 1996) and the bloom continued unabated for another 3 years. Feeding by adult grazers, such as dwarf surfclam, *Mulinia lateralis,* was apparently unaffected by the bloom (Montagna et al., 1993). However, both growth rates and swimming speed were reduced in the larvae of the polychaete *Streblospio benedicti* supporting the hypothesis that reduced populations of benthic organisms were caused by sublethal effects on larvae (Ward et al., 2000).

Although the brown tide may have impacted bay scallop populations in the upper Laguna Madre, they were also absent from other bays that did not experience brown tides during the same period of time (e.g. Corpus Christi Bay, Aransas Bay). In addition, scallops were present in the lower Laguna Madre during nearly every year of the 1990's. It seems just as likely that the absence of bay scallops in the upper Laguna Madre 1991–97 was due to natural variability,

rather than the direct or indirect impacts of the brown tide.

In conclusion, the low and variable abundance of bay scallops in Texas coastal bays and their apparent rarity in the bays along the rest of the northwestern Gulf precludes development of a fishery. In Texas, scallops are most abundant in the Laguna Madre, where seagrass cover is extensive and where salinities generally exceed 35 psu. Boom–bust population cycles are the norm in most bays, but especially in upper Laguna Madre, with booms occurring at intervals of 10–15 years over the last 60 years, based on the available data. This pattern suggests that Texas bay scallops are recruitment limited and that exogenous larval inputs must be very low.

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### Literature Cited

Ambrose, W. G., and E. A. Irlandi. 1992. Height of attachment on seagrass leads to trade-off between growth and survival in the bay scallop *Argopecten irradians*. Mar. Ecol. Prog. Ser. 90:45–51.

Barry Vittor and Associates, Inc. 2005. Historical SAV distribution in the Mobile Bay National Estuary Program area and ranking analysis of potential SAV restoration sites. Mobile Bay Natl. Estuary Prog., Mobile, 13 p.

Bricelj, V. M., and D. J. Lonsdale. 1997. *Aureococcus anophagefferns*: causes and ecological consequences of brown tides in U.S. mid-Atlantic coastal waters. Limnol. Oceanogr. 42:1,023–1,038.

Brock, D. B. 1983. Primary and secondary bay production. *In* L. Byrd and C. Chandler (Editors), Laguna Madre Estuary: a study of the influence of freshwater inflows, chapter VII, p. VII-1–VII-28. Rep. LP-182, Tex. Dep. Water Res., Austin.

Calnan, T. R. 1980. Molluscan distribution in Copano Bay, Texas. Rep. Invest. 103, Bur. Econ. Geol., Univ. Tex., Austin, 71 p.

Campbell, T. N. 1947. The Johnson Site: type site of the Aransas focus of the Texas Coast. Bull. Tex. Archeol. Paleo. Soc. 18:40–75.

Castiglione, M. C. 1983. The distribution and ecology of the molluscs of Corpus Christi Bay, Texas. M.S. thesis, Corpus Christi State Univ., Corpus Christi, 97 p.

Chaney, A. H. 1988. An analysis of nekton and plankton around a shoalgrass bed in the Laguna Madre of Texas. Padre Island Natl. Seashore, Contract # PX7490-7-0009, Corpus Christi, 156 p.

Circé, R. 1979. A seasonal study of seagrass colonization at a dredged material disposal site in upper Laguna Madre, Texas. M.S. thesis, Corpus Christi State Univ., Corpus Christi, 61 p.

Cosper, E. M., E. J. Carpenter, and M. Cottrell. 1989. Primary productivity and growth dynamics of the "brown tide" in Long Island embayments. *In* E. M. Cosper, E. J. Carpenter, and M. Bricelj (Editors), Novel phytoplankton blooms: causes and impacts of recurrent brown tides and other unusual blooms, p. 13o–158. Springer Verl., N.Y.

Culbertson, J., L. Robinson, P. Campbell, and L. Butler. 2004. Trends in Texas commercial fishery landings, 1981–2001. Tex. Parks Wild. Dep. Manage. Data Ser. 224, 140 p.

Davidson, J. E. 2002. Effects of propeller scarring on molluscan community structure in seagrass meadows of Redfish Bay, Texas. M.S. thesis, Texas A&M Univ.-Corpus Christi, Corpus Christi, 167 p.

Drumright, A. 1989. Seasonal variation in diversity and abundance of faunal associates of two oyster reefs within a south Texas estuarine complex. M.S. thesis, Corpus Christi State Univ., Corpus Christi, 150 p.

Eckman, J. E. 1987. The role of hydrodynamics in recruitment, growth, and survival in *Argopecten irradians* (Lamark) and *Anomia simplex* (D'Orbigny) within eelgrass meadows. J. Exp. Mar. Biol. Ecol. 106:165–191.

Evermann, B. W., and W. C. Kendall. 1894. The fishes of Texas and the Rio Grande Basin, considered chiefly with reference to their geographic distribution. Bull. U.S. Fish Comm. 12:57–126.

Gagliano, S. M., and R. T. Saucier. 1963. Poverty Point sites in southeastern Louisiana. Am. Antiq. 28:320–327.

Gallager, S. M., D. K. Stoecker, and V. M. Bricelj. 1989. Effects of the brown tide alga on growth, feeding physiology and locomotory behavior of scallop larvae (*Argopecten irradians*). *In* E. M. Cosper, E. J. Carpenter, and M. Bricelj (Editors), Novel phytoplankton blooms: causes and impacts of recurrent brown tides and other unusual blooms, p. 511–541. Springer Verl., N.Y.

Gutsell, J. S. 1930. Natural history of the bay scallop. Bull. U.S. Bur. Fish. 46:569–632.

Handley, L. R. 1995. Seagrass distribution in the northern Gulf of Mexico. *In* E. T. LaRoe, G. S. Farris, C. E. Puckett, P. D. Doran, and M. J. Mac (Editors), Our living resources: a report to the nation on the distribution, abundance and health of U.S. plants, animals and ecosystems, p. 273–275. U.S. Dep. Inter., Natl. Biol. Serv., Wash., D.C.

Harper, D. E., Jr. 1973a. Fauna of the margins of the Aransas National Wildlife Refuge. *In* Environmental impact assessment of shell dredging in San Antonio Bay, Texas, vol. 5, app. C3-A, p. 43–108. Texas A&M Res. Found., College Station.

________ . 1973b. The distribution of benthic and nektonic organisms in undredged control areas. *In* Environmental impact assessment of shell dredging in San Antonio Bay, Texas, vol. 3, app. B10-A, p. 1–157. Texas A&M Res. Found., College Station.

Henderson, W. G., L. C. Anderson, and C. R. McGimsey. 2002. Distinguishing natural and archaeological deposits: stratigraphy, taxonomy and taphonomy of Holocene shell-rich accumulations from the Louisiana Chenier Plain. Palaios 17:195–205.

Hester, T. R. 1971. Loyola Beach: an example of aboriginal adaptation to the maritime environment on the lower Texas Coast. Fla. Anthropol. 24(3):91–106.

Hicks, D. 1993. Effects of the December 1989 freeze on seagrasses and associated bivalve mollusca in Laguna Madre. M.S. thesis, Texas A&M Univ.-Corpus Christi, Corpus Christi, 58 p.

Hicks, D. W., C. P. Onuf, and J. W. Tunnell, Jr. 1998. Response of shoal grass, *Halodule wrightii*, to extreme winter conditions in the Lower Laguna Madre, Texas. Aquat. Bot. 62:107–114.

Hildebrand, H., and D. King. 1973. A preliminary biological study of the Cayo del Oso and the Pita Island area of the Laguna Madre: annual report before power plant operation 1972–73. Central Power Light Co., Corpus Christi, Tex., 333 p.

________ and ________ . 1974. A biological study of the Cayo del Oso and Pita Island area of the Laguna Madre: annual report 1973–74. Central Power Light Co., Corpus Christi, Tex., 233 p.

________ and ________ . 1975. A biological study of the Cayo del Oso and Pita Island area of the Laguna Madre: annual report 1974–75. Central Power Light Co., Corpus Christi, Tex., unpagin.

________ and ________ . 1976. A biological study of the Cayo del Oso and Pita Island area of the Laguna Madre: annual report 1975–76. Central Power Light Co., Corpus Christi, Tex., no sequential pg. no.

________ and ________ . 1977. A biological study of the Cayo del Oso and Pita Island area of the Laguna Madre: annual report 1976–77. Central Power Light Co., Corpus Christi, Tex., no sequential page numbers.

________ and ________ . 1979. A biological study of the Cayo del Oso and Pita Isalnd area of the Laguna Madre: final report 1972–78. Central Power Light Co., Corpus Christi, Tex., no sequential page numbers.

Holland, J. S., N. J. Maciolek, R. D. Kalke, and C. H. Oppenheimer. 1974. A benthos and plankton study of the Corpus Christi, Copano and Aransas bay systems II: report on data collected during the period July 1973–April 1974. Univ. Tex. Mar. Sci. Inst., Port Aransas, 121 p.

Hubner, M. W. 2007. Recruitment of bay scallops (*Argopecten irradians*) and other byssate bivalves in the upper Laguna Madre, Texas. M.S. thesis, Texas A&M Univ.-Corpus Christi, Corpus Christi, 64 p.

Ladd, H. S. 1951. Brackish-water and marine assemblages of the Texas coast, with special reference to mollusks. Publ. Inst. Mar. Sci., Univ. Tex. 2(1):127–164.

Marshall, N. 1947. An abundance of bay scallops in the absence of eelgrass. Ecology 28:321–322.

Martin, C. 1994. Corpus Christi Bay and La Quinta Channel: a comparison of benthic diversity. M.S. thesis, Texas A&M Univ.-Corpus Christi, Corpus Christi, 81 p.

Martinez-Andrade, F., P. Campbell, and B. Fuls. 2005. Trends in relative abundance and size of selected finfishes and shellfishes along the Texas coast: November 1975–December 2003. Tex. Parks Wild. Dep. Manage. Data Ser. No. 232, Austin, 128 p.

Montagna, P. A. 1993. Comparison of ecosystem structure and function of created and natural seagrass habitats in Laguna Madre, Texas. Univ. Tex. Mar. Sci. Inst. Tech. Rep., TR/93-007, Port Aransas, 72 p.

________ and C. Martin. 1994. La Quinta Channel environmental monitoring project: benthic diversity. Univ. Tex. Mar. Sci. Inst. Tech. Rep., TR/94-003, Port Aransas, 142 p.

________, D. A. Stockwell, and R. D. Kalke. 1993. Dwarf surfclam *Mulinia lateralis* (Say, 1822) populations and feeding during the Texas brown tide event. J. Shellfish Res. 12:433–442.

Newcomb, W. W. 1961. The indians of Texas: from prehistoric to modern times. Univ. Tex. Press, Austin, 440 p.

Onuf, C. P. 1995. Seagrass meadows of the Laguna Madre of Texas. *In* E. T. LaRoe, G. S. Farris, C. E. Puckett, P. D. Doran and M. J. Mac (Editors), Our living resources: a report to the nation on the distribution, abundance and health of U.S. plants, animals and ecosystems, p. 275–277. U.S. Dep. Inter., Natl. Biol. Serv., Wash., D.C.

________. 1996. Seagrass responses to long-term light reduction by brown tide in upper Laguna Madre, Texas: distribution and biomass patterns. Mar. Ecol. Prog. Ser. 138:219–231.

Parker, R. H. 1959. Macro-invertebrate assemblages of central Texas coastal bays and Laguna Madre. Bull. Am. Assoc. Pet. Geol. 43:2100–2166.

Pearce, J. J. 2003. Benthic community relationship to seagrass cover, upper Laguna Madre and Baffin Bay, Texas. M.S. thesis, Texas A&M Univ.-Corpus Christi, Corpus Christi, 131 p.

Peterson, C. H., and H. C. Summerson. 1992. Basin-scale coherence of population dynamics of an exploited marine invertebrate, the bay scallop: implications of recruitment limitation. Mar. Ecol. Prog. Ser. 90:257–272.

Powell, E. N., R. J. Stanton, Jr., H. Cummins, and G. Staff. 1982. Temporal fluctuations in bay enviroments: the death assemblage as a key to the past. *In* J. R. Davis (Editor), Proceedings of the symposium on recent benthological investigations in Texas and adjacent states, p. 203–232. Tex. Acad. Sci., Austin.

Prewitt, E. R., and J. G. Paine. 1987. The Swan Lake Site (41AS16) on Copano Bay, Aransas County, Texas: settlement, subsistence and sea level. Bull. Tex. Arch. Soc. 58:147–174.

Pulich, W., Jr. 1999. Introduction. *In* Seagrass conservation plan for Texas, p. 14–25. Tex. Parks Wild. Dep., PWD BK R0400-041 (4/99), Austin.

Ricklis, R. A. 1987. Archeological investigations at the McKinzie Site (41NU221), Nueces County, Texas: description and contextual interpretations. Bull. Tex. Archeol. Soc. 58: 1–76

________. 1993. A model of environmental and human adaptive change on the central Texas coast: geoarchaeological investigations at White's Point, Nueces Bay and surrounding area. Coastal Archaeological Studies, Inc., Corpus Christi.

________. 1995. Prehistoric occupation of the central and lower Texas coast: a regional overview. Bull. Tex. Archeol. Soc. 66:265–300

________. 1996. The Karankawa Indians of Texas. Univ. Tex. Press, Austin, 222 p.

________. 2006. Archeological testing at the McGloin Bluff Site, 41SP11, San Patricio County, Texas. Curr. Archaeol. Tex. 8(1):9–17.

________ and B. M Albert. 2005. Testing at 41AS5 on Swan Lake, central Texas Coast: a summary of the human-ecological implications. Curr. Archaeol. Tex. 7(1):12–17

________ and K. A. Cox. 1991. Toward a chronology of adaptive change during the Archaic of the Texas Coastal Bend. La Tierra 18(2):13–31.

Rickner, J. A. 1975. Seasonal variation of selected marine macro-fauna in a seagrass community bordering Stedman Island, Redfish Bay, Texas. M.S. thesis, Texas A&I Univ., Kingsville, 107 p.

________. 1979. The influence of dredged material islands in upper Laguna Madre, Texas, on selected seagrasses and macro-benthos. Ph.D. diss., Texas A&M Univ., College Station, 57 p.

Russo, M., and I. R. Quitmyer. 1996. Sedentism in coastal Populations of south Florida. *In* E.J. Reitz, L.A. Newsom, and S.J. Scudder (Editors), Case studies of environmental archaeology, p. 127–147. Plenum Press, N.Y.

Ruth, B. F. 1991. Establishment of estuarine faunal use in a salt marsh creation project, Nueces River Delta, Texas. M.S. thesis, Corpus Christi State Univ., Corpus Christi, 80 p.

Shafer, J. J., and C. L. Bond. 1985 (for 1983). An archeological review of the central Texas coast. Bull. Tex. Archeol. Soc. 54:271–286.

Shidler, J. K. 1960. Preliminary survey of invertebrate species. Tex. Game Fish Comm., Mar. Fish. Div. Job Rept., Proj. MO-1-R-2, Oyster Investigations, Area MO-1, Job B-2b, Austin, 15 p.

Smith, E. J. 1985. Paleoecologic aspects of modern macroinvertebrate communities of southern Laguna Madre, Texas. M. S. thesis, Stephen F. Austin Univ., Nacogdoches, 77 p.

Smith, H. A. 1986. Prehistoric settlement and subsistence patterns of the Baffin Bay area of the lower Texas coast. Ph.D. diss., South. Meth. Univ., Dallas, 173 p.

Steele, D. G. 1987. Utilization of marine mollusks by inhabitants of the Texas coast. Bull. Tex. Archeol. Soc. 58:215–248.

________ and E. R. Mokry, Jr. 1985 (for 1983). Archeological investigations of seven prehistoric sites along Oso Creek, Nueces County, Texas. Bull. Tex. Archeol. Soc. 54:287–308.

Tettlebach, S. T., and P. Wenczel. 1993. Reseeding efforts and the status of bay scallop *Argopecten irradians* (Lamarck, 1819) populations in New York following the occurrence of "brown tide" algal blooms. J. Shellfish Res. 12:423–431.

TPWD. 2002. Atlantic bay scallop: *Argopecten irradians amplicostatus* fact sheet. Tex. Parks Wild. Dep., Austin, 2 p.

________. 2006. Texas Parks and Wildlife outdoor annual hunting and fishing regulations, 2006–2007. Tex. Parks Wild. Dep., Austin, 112 p.

Tracey, G. A. 1988. Feeding reduction, reproductive failure, and mortality in *Mytilus edulis* during the 1985 "brown tide" in Narragansett Bay, Rhode Island. Mar. Ecol. Prog. Ser. 50:73–81.

Ward, L. A., P. A. Montagna, R. D. Kalke, and E. J. Buskey. 2000. Sublethal effects of Texas brown tide on Streblospio benedicti (Polychaeta) larvae. J. Exp. Mar. Biol. Ecol. 248:121–129.

White, W. A., T. R. Calnan, R. A. Morton, R. S. Kimble, T. G. Littleton, J. H. McGowen, and H. S. Nance. 1987. Submerged lands of Texas, Beaumont-Port Arthur area: sediments, geochemistry, benthic macroinvertebrates and associated wetlands. Bur. Econ. Geol., Univ. Tex., Austin, 110 p.

________, ________, ________, ________, ________, ________, and ________. 1989a. Submerged lands of Texas, Port Lavaca area: sediments, geochemistry, benthic macroinvertebrates and associated wetlands. Bur. Econ. Geol., Univ. Tex., Austin, 165 p.

________, ________, ________, ________, ________, ________, and ________. 1989b. Submerged lands of Texas, Kingsville area: sediments, geochemistry, benthic macroinvertebrates and associated wetlands. Bur. Econ. Geol., Univ. Tex., Austin, 137 p.

________, ________, ________, ________, ________, ________, and K. E. Schmedes. 1985. Submerged lands of Texas, Galveston–Houston area: sediments, geochemistry, benthic macroinvertebrates and associated wetlands. Bur. Econ. Geol., Univ. Tex., Austin, 145 p.

________, ________, ________, ________, ________, ________, and ________. 1986a. Submerged lands of Texas, Corpus Christi area: sediments, geochemistry, benthic macroinvertebrates and associated wetlands. Bur. Econ. Geol., Univ. Tex., Austin, 154 p.

________, ________, ________, ________, ________, ________, and ________. 1986b. Submerged lands of Texas, Brownsville–Harlingen area: sediments, geochemistry, benthic macroinvertebrates and associated wetlands. Bur. Econ. Geol., Univ. Tex., Austin, 138 p.

Wilhite, H. S., T. C. Allison, and J. A. Rickner. 1982. The diversity and distribution of living molluscs in the lower Laguna Madre of Texas. *In* J. R. Davis (Editor), Proceedings of the symposium on recent benthological investigations in Texas and adjacent states, p. 233–247. Tex. Acad. Sci., Austin.

Williamson, C. J. 1980. Population dynamics of molluscs in a seagrass bed surrounding a dredged material island, upper Laguna Madre, Texas. M.S. thesis, Corpus Christi State Univ., Corpus Christi, 81 p.

Zimmerman, R. J., and A. H. Chaney. 1969. Salinity decrease as an affecter of molluscan density levels in a turtle Grass (*Thalassia testudinum* König) bed in Redfish Bay, Texas. TAIUS 2(1):5–10.

# The Bay Scallop, *Argopecten irradians amplicostatus*, in Northeastern Mexico

ARMANDO T. WAKIDA-KUSUNOKI

## Introduction

The bay scallop, *Argopecten irradians amplicostatus*, has been present in low abundances in coastal lagoons in the northeastern Mexican States of Tamaulipas and Veracruz. Its distributional range extends from Laguna Madre, Tamaulipas, southward and ends in Tuxpan, Veracruz (Fay et al., 1983; Rodriquez-Castro, 2002). Rodriquez-Castro (2002) found shells of this species in six localities on the coast of Tamaulipas (Fig. 1), but no live scallops. This species was also present in Boca Tampachiche, a section of the Tamiahua Lagoon, Veracruz, before the mouth closed to the Gulf of Mexico (Roman Maya[1]).

Bay scallop harvests have been light and sporadic, and most scallops were taken for personal consumption. Fishermen retained scallops when harvesting oysters. The scallops were harvested only in Laguna Madre, Tamaulipas.

The clam fishery in the Mexican Gulf Coast lagoons is small and is based on brackish water clams, *Rangia* spp., and *Polymesoda caroliniana* (Wakida-Kusunoki and MacKenzie, 2004). The clam stocks are small probably because the mouths of the lagoons are semi-closed and unstable. As a consequence, the salinity is highly variable and a high mortality of clams and probably the bay scallops results when the salinity becomes too high (in the high 30's and 40's in ppt) (Drexel[2]). In the 1960's, Laguna Madre closed and its waters were hyperhaline (Garcia-Cubas, 1968).

## Historical Uses

Mollusks were used by the pre-Columbian cultures in Mexico as food, trade goods (Jimenez-Badillo, 1991), personal adornment (Suarez-Diez, 2002), religious items (Houston[3]) (Jimenez Badillo, 1991), building construction (Mackenzie and Wakida-Kusunoki, 1997; Stark, 2001), and making

[1]Roman Maya, Mauricio, Director of Ecology Department of Tampico Alto Municipality, Veracruz. Personal commun., 2005.

[2]Drexel, A. Fish distributor. La Pesca, Tamaulipas.

[3]Houston, S. D., H. Escobedo, P. Hardin, R. Ferry, D. Webster, M. Chile, C. Goleen, K. Emery, and D. Stuart. 1998. Investigaciones en Piedras Negras, Guatemala: Temporada de Campo 1998. Entre las Montañas y El Mar: Investigaciones en Piedras Negras, Guatemala. Fundacion para el avance de los estudios mesoamericanos. http://www.famsi.org/reports/97006es/section03.htm Access 10 Aug. 2006.

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*ABSTRACT—The bay scallop,* Argopecten irradians amplicostatus, *has been present in the coastal lagoons of northeastern Mexico from Laguna Madre, Tamaulipas, to Tuxpan, Veracruz. But now, usually scarce in all lagoons, the scallop is harvested sporadically by fishermen who wade and collect them by hand and with tongs. Some are eaten by the fishermen and some are sold. They bring the fishermen about 60 pesos (5.88US$)/kg. Only the adductor muscles are eaten; they are prepared in cocktails and in ceviche. Little evidence exists that this scallop species was used in the early Mexican cultures.*


Figure 1.—Locations where bay scallops, *Argopecten irradians amplicostatus*, have been reported.

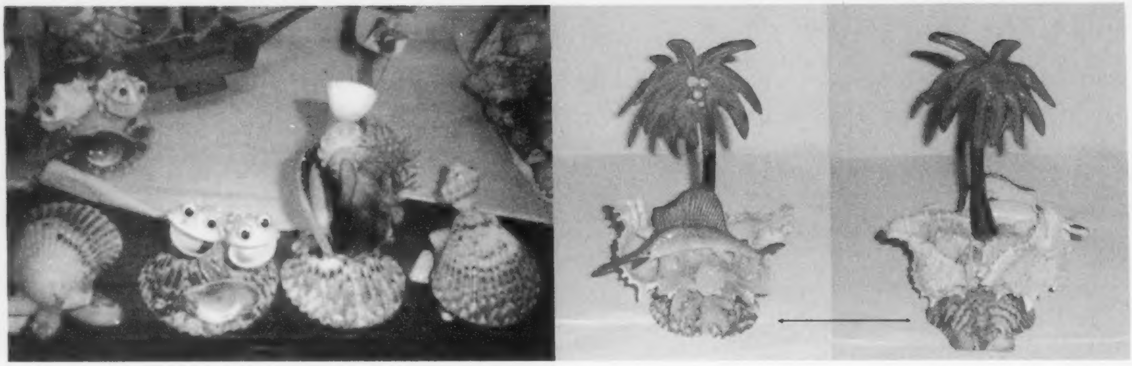

Figure 2.—Handcrafts made with a pectinid shells. The arrows show the shell of *Argopecten gibbus*. Photograph by Armando T. Wakida-Kusunoki and Ubaldo Roman Hernandez.

music (Clark[4]). Pectinid shells, but not shells of *A. i. amplicostatus*, were represented in Aztec icons of liturgical scenes (Kubler[5]), and they have been found as Aztec tributes in the Templo Mayor in Mexico City (Jimenez Badillo, 1991), and as Mayan tributes in Tikal, Guatemala (Laporte[6]) (Borhegyi, 1966). Little evidence exists that *A. i. amplicostatus* was used by the early cultures in Mexico.

Pectinid shells nowadays are used in handcrafts (Fig. 2). In Catholicism, the shells are a symbol of baptism and sometimes a shell is used to pour the baptismal water (Fig. 3).

### Harvesting Methods

Bay scallops were harvested only in Mezquital and Carboneras, Tamaulipas, but the scallop beds near Mezquital, Tamaulipas, were destroyed during the passage of Hurricane Emily in July 2005 (Rivera[7]). The fishermen, all of whom are males with low incomes, intersperse scallop and oyster harvests. Mezquital, in the northern part of the Mexican Laguna Madre, supports about 10 fishermen, who are from 16 to 60 years old. The fishermen get to the shellfish beds in fiberglass boats about 7.6 m long and propelled by 15 hp outboard motors. Each boat carries 2–3 fishermen who share the boat expenses. They harvest oysters and bay scallops while wading in shallow waters. They feel for the bay scallops with their feet and collect them with their hands or short oyster tongs (Rivera[7], Garcia [8]) (MacKenzie and Wakida, 1997) (Fig. 4).

Bay scallop harvesting was done only in June and then only about once a week, the effort being governed by market demand. The harvesting days were only when the water was sufficiently warm to allow fishermen to wade. They usually harvested bay scallops for about 5 hours (9 a.m.–2 p.m.) each day, and each could harvest as many as 200 scallops/hour. No landing statistics of bay scallops in the Mexican coast of the Gulf exist because there is no fisherman licensing or reporting requirement for bay scallops.


Figure 3.—Items used in Catholic baptisms. Photograph by Armando T. Wakida-Kusunoki.

### Markets and Marketing

Fishermen sold the adductor muscles of the bay scallops, which were obtained only after cooking the whole scallop. They were sold along with oysters to tourists and to small dealers who transport marine products to Matamoros, 70 km away, and to Reynosa, 270 km away. In 2005, the buyers paid fishermen 60 pesos (5.88US$)/kg of bay scallop muscles. A kilogram con-

[4]Clark, M. 1996. Some basics on shell trumpets and some very basics on how to make them. http://www.furious.com/perfect/shells.html, accessed 10 Aug. 2006.

[5]Kubler, G. 1972. Jaguars in the Valley of Mexico. *In* E. P. Benson (Editor), The cult of the feline, conference in pre-Columbian iconography. Dumbarton Oaks Res. Library and Collections trustees for Harvard University, Wash., D.C., p. 19–50. Avail online at http://www.doaks.org/Feline_pgs.PDF, accessed 10 August 2006.

[6]Laporte, J. P. 2004. Exploración y restauración en la plataforma este del mundo perdido, Tikal (estructuras 5D-83 a 5D-89) XVIII. *In* J. P. LaPorte, B. Arroyo, and H. E. Mejía (Editors), Simposio de investigaciones arqueológicas en Guatemala. Museo Nacional de Historia y Etnografía. Guatemala. Avail online at http://www.famsi.org/reports/03101es/13laporte/13laporte.pdf, accessed 10 Aug. 2006.

[7]Rivera, Noe. Oyster and scallop fishermen. Mezquital, Tamaulipas. Personal. commun., 2006.

[8]Garcia, Leobardo, biologist, Biology Research Station in Carboneras, Tamaulipas. Personal commun., Aug. 2006.

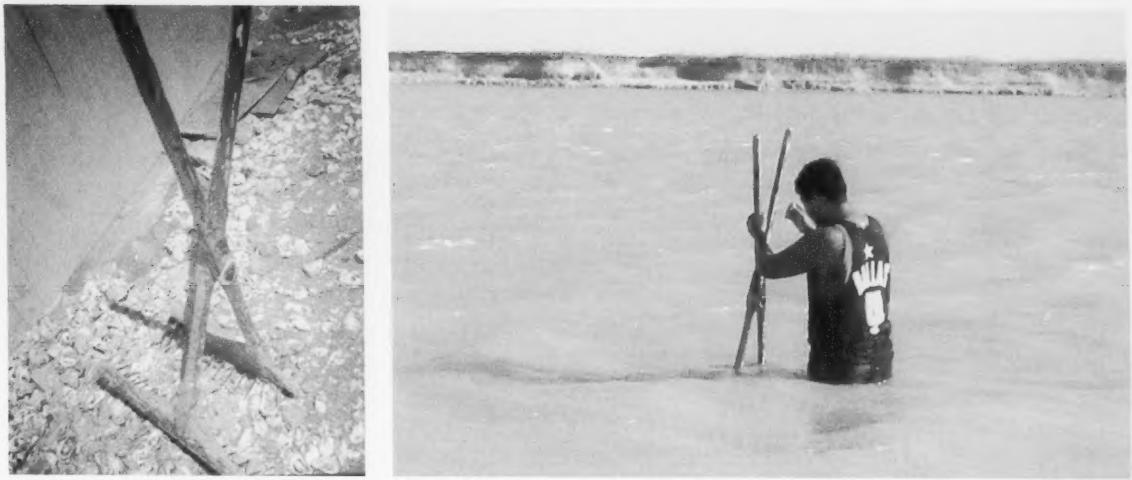

Figure 4.—Harvesting bay scallops in Laguna Madre. Photograph by Leobardo Garcia Solorio.

tains about 500 bay scallop muscles. Each fisherman earned 120–150 pesos (US$11.76–$14.70)/day.

### Local consumption

Bay scallop muscles usually were prepared in cocktails: boiled scallops were combined in a glass with lemon juice, onion, chili, oil, salt, ketchup, hot pepper, and coriander. In ceviche, the scallops were cooked with lemon juice, onion, chili, oil, and salt (Hernandez Peña[9]).


### Acknowledgments

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[9]Hernandez Peña, A. President of fishing cooperative "Boca Ciega" Matamoros, Tamaulipas. Personal commun., Nov. 2005.

### Literature Cited


Borhegyi, S. F. 1966. Shell offerings and the use of shell motifs at Lake Amatitlan and Teotihuacan. XXXVI Int. Congr. Am. Act I: 355–371. Sevilla, Spain.

Fay, C. W., R. J. Neves, and G.B. Pardue. 1983. Species profiles: life histories and environmental requirements of coastal fishes and invertebrates (Mid-Atlantic)—bay scallop. U.S. Fish Wildl. Serv., Div. Biol. Serv., FWS/OBS-82/11.12. U.S. Dep. Inter., Army Corps Eng.: TR EL-82-4, 17 p.

Garcia-Cubas, A. Jr. 1968. Ecología y distribución de los micromoluscos recientes de la Laguna Madre, Tamaulipas, México. UNAM, Inst. Geol. Bol. 86:1–44.

Jiménez Badillo, D. 1991. Malacología del Templo Mayor a partir de los datos de la ofrenda H. *In* O. J. Polanco (Editor), La fauna en el Templo Mayor, p. 171–211. GV Editores-Asociación de Amigos del Templo Mayor. Colección Divulgación, Mexico.

MacKenzie, C. L., Jr. and A. T. Wakida-Kusunoki. 1997. The oyster industry of eastern Mexico. Mar. Fish. Rev. 59(3):1–13.

Rodríguez- Castro, J. H. 2002. Sistemática y zoogeografía de los gastrópodos y bivalvos marinos de la costa del estado de Tamaulipas, México. Masters Thesis, Inst. Tecnol. Ciudad Victoria, Ciudad Victoria, Tamaulipas, 249 p.

Stark, B. L. 2001. Classic period Mixtequilla, Veracruz, Mexico: diachronic inferences from residential investigations. Inst. Meso-Am. Stud., Monogr. 12, Univ. Albany, SUNY, 411 p.

Suarez-Diez, L. 2002. Tipología de los objetos prehispánicos de concha. Inst. Nacional Antropol. Hist. Mexico, D.F., 2nd ed., 235 p.

Wakida-Kusunoki, A. T., and C. L. MacKenzie, Jr. 2004. Rangia and marsh clams, *Rangia cuneata*, *R. flexuosa*, and *Polymesoda caroliniana*, in eastern Mexico: distribution, biology and ecology, and historical fisheries. Mar. Fish. Rev. 66(3):13–20.

# The Status of Eelgrass, *Zostera marina*, as Bay Scallop Habitat: Consequences for the Fishery in the Western Atlantic

MARK S. FONSECA and AMY V. UHRIN

*ABSTRACT—*Zostera marina *is a member of a widely distributed genus of seagrasses, all commonly called eelgrass. The reported distribution of eelgrass along the east coast of the United States is from Maine to North Carolina. Eelgrass inhabits a variety of coastal habitats, due in part to its ability to tolerate a wide range of environmental parameters. Eelgrass meadows provide habitat, nurseries, and feeding grounds for a number of commercially and ecologically important species, including the bay scallop,* Argopecten irradians. *In the early 1930's, a marine event, termed the "wasting disease," was responsible for catastrophic declines in eelgrass beds of the coastal waters of North America and Europe, with the virtual elimination of Z.* marina *meadows in the Atlantic basin. Following eelgrass declines, disastrous losses were documented for bay scallop populations, evidence of the importance of eelgrass in supporting healthy scallop stocks.*

*Today, increased turbidity arising from point and non-point source nutrient loading and sediment runoff are the primary threats to eelgrass along the Atlantic coast and, along with recruitment limitation, are likely reasons for the lack of recovery by eelgrass to pre-1930's levels. Eelgrass is at a historical low for most of the western Atlantic with uncertain prospects for systematic improvement. However, of all the North American seagrasses, eelgrass has a growth rate and strategy that makes it especially conducive to restoration and several states maintain ongoing mapping, monitoring, and restoration programs to enhance and improve this critical resource. The lack of eelgrass recovery in some areas, coupled with increasing anthropogenic impacts to seagrasses over the last century and heavy fishing pressure on scallops which naturally have erratic annual quantities, all point to a fishery with profound challenges for survival.*

## Description of the Plant

*Zostera marina* L. is one of a small genus of widely distributed seagrasses, all commonly called eelgrass (Fig. 1). This genus contains twelve species worldwide but only three species are found in North America (*Z. asiatica* and *Z. japonica* on the west coast) with *Z. marina* as the only confirmed native species. Eelgrass is found on sandy substrates or in estuaries, and rarely on the open ocean coastline and then, usually, in the shelter of boulders or other similarly immobile structures.

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The plant is almost always submerged or partially floating at low tide. In the western Atlantic it is only occasionally intertidal (Fig. 2).

However, eelgrass is actually not a grass—it is in the same Class grouping as other monocotyledonous plants, but it then branches into strictly aquatic plant groups at lower taxonomic levels:

Phylum: Anthophyta (flowering plants),
Class: Liliopsida (monocots),
Order: Potamogetonales,
Family: Zosteraceae (Greek 'zoster,' meaning 'belt'),
Genus/species: *Zostera marina*.
Authority: Linnaeus, 1758.

A summary of the key identification features are as follows:

Relatively thin, flattened, blade-like leaves up to ~ 1 cm in width, dark green in color;

Leaves usually 20–50 cm but up to 2 m in length, 4–10 mm wide, with 5–11 veins and rounded leaf tips, sometimes with a very small, sharp point;

Leaf sheath forms an envelope around the aboveground stem;

Reproductive shoot, terminal, branched, and substantially longer than vegetative shoots;

Seeds ovoid or ellipsoid, ~2–3 mm long with 16–25 distinct ribs;

Rhizome color (when living) is dark brown and has a polished appearance;

At each rhizome node, there are typically two root bundles;

Branching is alternate along the rhizome and frequently irregular; each branch becomes an independent shoot.

To the casual observer there is little morphological difference between the two seagrass species that co-occur with eelgrass in the western Atlantic, shoal grass, H*alodule wrightii* Aschers, and widgeon grass, *Ruppia maritima* L. However, the three species can be distinguished particularly by their blade tips and rhizomes (Fig. 3). The leaf tip of eelgrass is round, sometimes with a very small apical point, whereas *H. wrightii* has a bicuspidate (crowned) appearance

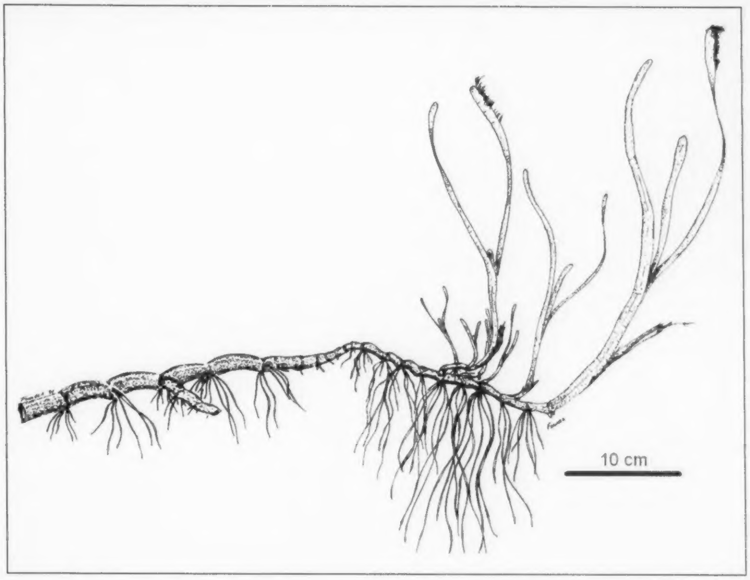


Figure 1.—*Zostera marina* (eelgrass) showing the whole plant structure.

Figure 2.—Eelgrass bed in Long Island Sound (Photograph by C. Pickerell).

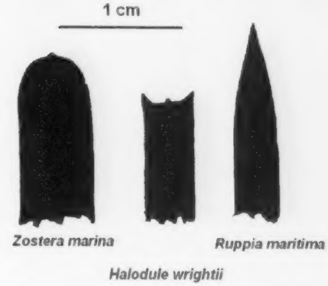


Figure 3.—Sketches of blade tips for the three cogeners. Reproduced from Thayer et al., 1984.

and *R. maritima* is lancelate (pointed). Also, the living rhizome of eelgrass is brown while the rhizomes of the other species are much lighter, almost white depending on sediment type.

Eelgrass is unlike all the other native North American seagrass species in that each seagrass shoot is a "terminal shoot"; that is, it is always located at the end of the rhizome. There are no shoots left behind, rooted in place as with the other seagrass species—instead the terminal shoot actually migrates across the seafloor leaving a trail of rhizome rooted in place behind it which gives the plant unusual pattern development capabilities and high spatial recolonization rates.

The life history of eelgrass has been well-described for almost a century (Setchell, 1929). The plant typically follows a 2-year (perennial) life history (Fig. 4). For most of the range in the western Atlantic, eelgrass seeds germinate in the late winter and grow vegetatively through the summer, creating daughter shoots (ramets) almost continuously every 2–4 weeks. These clones then over-winter in a slow growth phase. In the second year of their existence, shoots of that age undergo a dramatic alternation of generation and transform into luxurious flowering structures that produce dozens of seeds. After setting seed, the shoot dies. Seeds tend to stay very near the parent plant yet the role of seeding in eelgrass bed maintenance remains somewhat of a mystery.

Like terrestrial plants, there appears to be "mast years" where extraordinary numbers of seedlings germinate which can result in significant new bed formation in locations otherwise long devoid of cover. Flowering stalks can break off and float for many miles (Phillips and Meñez, 1988; Harwell and Orth, 2002), providing a means for colonization at far distant locations.

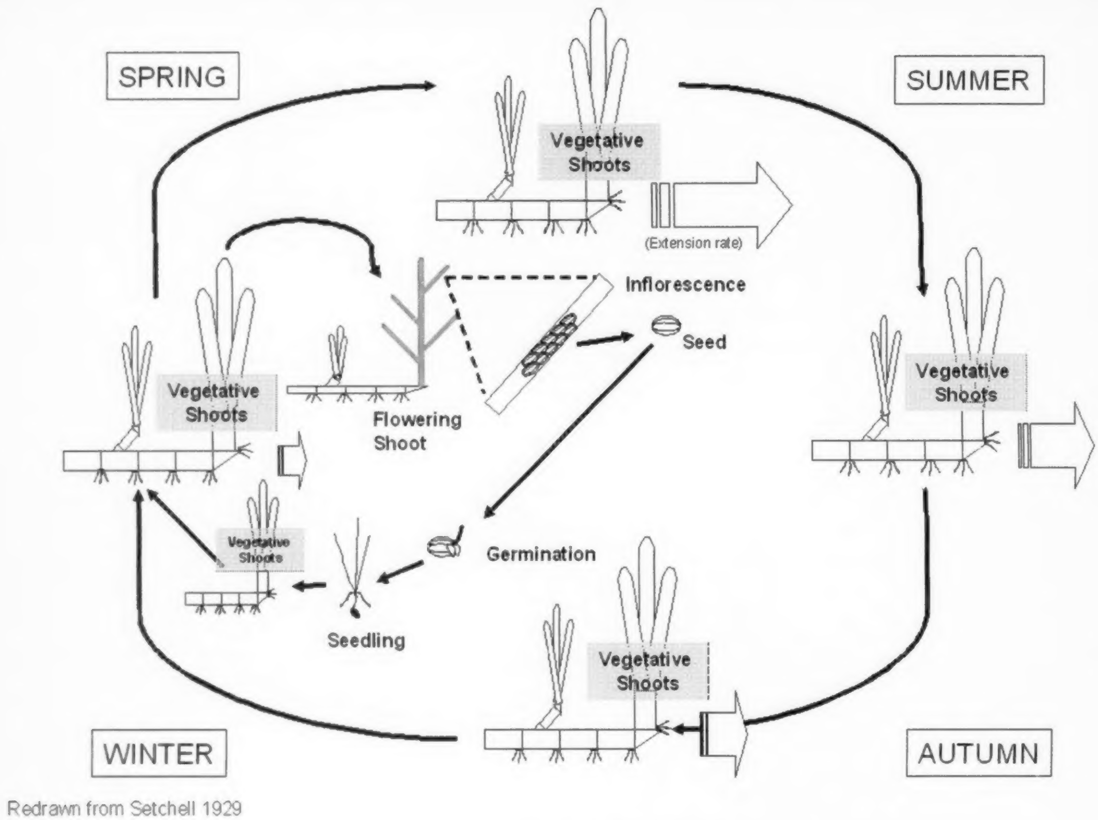


Figure 4.—Stylized life history of perennial eelgrass. Redrawn from Setchell, 1929.

### Limiting Factors

Eelgrass inhabits a wide range of coastal habitats, due in part to its ability to tolerate a wide range of environmental parameters. These parameters are discussed in more detail below.

#### Substrate

Eelgrass is limited to unconsolidated sediments, and thus, comparatively quiescent environments. However, luxurious eelgrass beds may be found clinging to cobble sediments behind highly exposed islands along the New England coast.

#### Light / Depth

Eelgrass is limited in its depth distribution by light at depth and emersion at its upper limit. The emersion tolerance of eelgrass is not well quantified, but observations indicate that it has a low desiccation tolerance and thus cannot withstand prolonged exposure at low tide unless the environment is cool (typically below 20°C) and a film of water persists to keep the plant wetted. When exposed to truly dry conditions and a mild breeze, eelgrass blades can desiccate beyond recovery in minutes while the sheath bundle, which contains the meristems, may withstand much longer periods of true desiccation (Fonseca[1]).

Eelgrass is generally limited to depths where light is at least 15–25% of surface irradiance (Dennison, 1987; Gallegos, 1994) but these values are undergoing re-evaluation (Kenworthy[2]). Depth distribution of eelgrass varies with water quality on a local scale. For example, in both Chesapeake Bay and the North Carolina coastal zone, where waters can be turbid, eelgrass is usually limited to depths of 2 m or less (Dennison et al., 1993; Ferguson and Korfmacher, 1997; Fonseca et al., 2002; Kemp et al., 2004). In contrast, further north, estuaries become less turbid and light is able to penetrate to greater depths, with eelgrass growing in excess of 10 m in some areas (Maquoit Bay, ME:

[1]Fonseca, M. Unpubl. data. NOAA, Center for Coastal Fisheries and Habitat Research, Beaufort, N.C.

[2]Kenworthy, J. NOAA, Center for Coastal Fisheries and Habitat Research, Beaufort, N.C. Personal commun., 2009.

Short and Short, 2003; Fort Weatherall, Jamestown, R.I.: Fonseca[1]). Moreover, the periodicity of light-reducing events (acute versus chronic diminishment of light) may play a significant yet difficult-to-detect role in the distribution of eelgrass. Moore et al. (1997) found that a month-long elevated turbidity event at a site in Chesapeake Bay caused eelgrass to die off, an event that was otherwise very difficult to detect using data averaged over longer periods of time.

### Temperature

Due to its widespread distribution, eelgrass can experience water temperature fluctuations from less than 0°C to greater than 30°C. Although eelgrass may grow at temperature extremes, physiological processes within the plant (i.e. photosynthesis, respiration) require a more limited range for optimum performance (Fig. 5; Penhale, 1977; Evans et al., 1986, Marsh et al., 1986). Although there are a number of factors to consider, it is widely considered that a sustained temperature approaching 25°C is the upper tolerance limit for eelgrass (Zimmerman et al., 1989; Bintz et al., 2003).

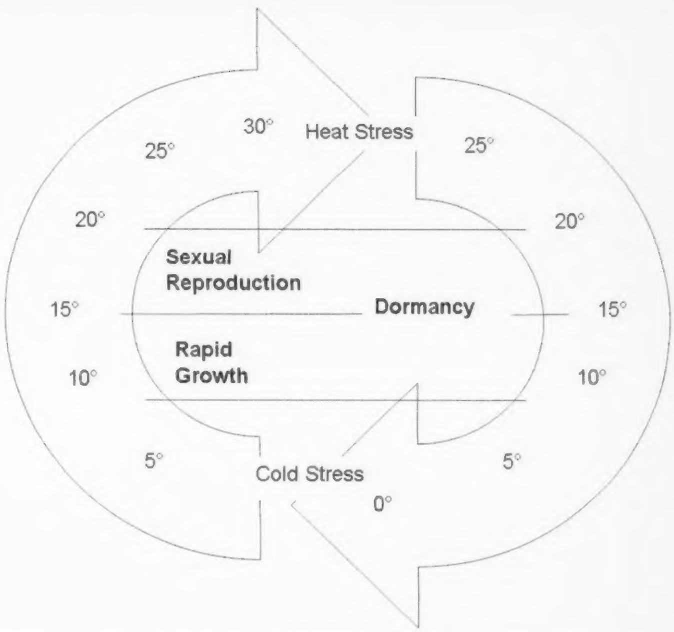


Figure 5.—Graphic illustration of Setchell's topology describing the relationship between temperature and eelgrass phenology. Redrawn from Setchell, 1929.

### Water Motion

Eelgrass beds thrive in areas of moderate to high current speeds and can withstand current speeds of up to 1.5 m/s (Fonseca and Fisher, 1986; Koch, 2001). Water motion plays a role in structuring eelgrass meadows (Fonseca and Bell, 1998). Scouring by waves and currents at the leading edges of a meadow can erode sediments and plants and prevent sediment deposition. In some instances, large quantities of sediment may actually be carried off and deposited, burying significant portions of existing meadows which have limited burial tolerance (covering ~50% of the leaves kills the plants; Mills and Fonseca, 2003).

Eelgrass is effective in damping out waves and reducing current velocities within the canopy as water passes through the meadow, especially when the canopy extends to the water's surface (Fonseca et al., 1983; Fonseca and Cahalan, 1992). As a wave passes through the meadow, eelgrass shoots wave in synchrony with the passing crests (Grizzle et al., 1996) and troughs and create drag that diminishes waves rapidly especially if the plants occupy most of the water column. Under tidal currents, an eelgrass canopy will bend into a compact layer as current velocities increase. By deflecting water over it, the canopy shields the bottom from erosive forces.

### Salinity

Eelgrass is euryhaline; it has been reported from areas experiencing periods of nearly fresh water to full-strength seawater or greater (Thayer et al., 1984). An optimum salinity for this species has, to our knowledge, never been determined, but photosynthesis virtually ceases below 10‰ and is probably optimal at oceanic salinity levels (approximately 32‰). Given the generally estuarine distribution of eelgrass, the importance of periodic freshwater events may play a significant role in periodically resetting its distribution.

### Nutrients

Eelgrass growth, abundance, and morphology are clearly linked to available nutrient pools (Short 1983a, b, 1987). In the siliceous sedimentary environment typical of temperate eelgrass beds, plants appear to be nitrogen limited (Short, 1987 and references therein) but typically have ample supplies of phosphorous (McRoy and Barsdate, 1970; McRoy et al., 1972). Nutrients are absorbed from the sediment and associated interstitial water at the roots and are subsequently transferred to the rest of the plant. In addition, plant leaves are able to absorb nutrients from the water column.

## The Wasting Disease

In the early 1930's, a marine event of near catastrophic proportions occurred in eelgrass beds of the coastal waters of North America and Europe. Within two years of its first observation, the "wasting disease," as it was termed, had eliminated over 90% of eelgrass

populations worldwide (Muehlstein, 1989). Total losses along the Atlantic coast of the United States cannot be quantified as systematic documentation of eelgrass distribution did not exist prior to the 1930's. Although often suspected, decades later the marine slime mold, *Labyrinthula zosterae*, was suggested as the responsible pathogen (Muehlstein et al., 1991). However, the actual conditions leading to the widespread outbreak have never been clearly determined. One long-held contention is that climatic shifts, particularly a sudden increase in water temperature and reduced incoming solar radiation in the 1930's led to increased susceptibility of eelgrass to infection through the influence of these abiotic factors on seagrass metabolism and photobiology (Tutin, 1938; Rasmussen, 1977). The controversy over the cause of the wasting disease, particularly in lieu of numerous studies regarding thermal tolerance and light requirements of *Z. marina*, and a paucity of good meteorological data for the early 20th century, is debated even today.

Eelgrass recovery was not apparent before the mid 1950's. By the 1960's, eelgrass populations had generally re-established and 30–40 years later had largely recovered, although many locations which once supported thriving eelgrass habitat have never recolonized (Short et al., 1988, 1993; Short and Short, 2003). It is believed that those populations inhabiting lower salinity environments (upper reaches of estuaries) were able to avoid infection and thus provide a stock of plants for recovery as salinity clearly plays a role in regulating *L. zosterae* activity, with reduced activity below 20–25‰ (Muehlstein et al., 1988, Burdick et al., 1993). Although a large-scale event akin to that of the 1930's has not occurred in recent history, symptoms and epidemiology of this alleged disease have manifested themselves in local eelgrass populations in the mid 1980's and may be associated with some small-scale die-offs (Short et al., 1986, 1987, 1988).

Following the virtual elimination of *Z. marina* meadows along the eastern seaboard, catastrophic population declines were documented for bay scallop, *Argopecten irradians*, populations (see review in MacKenzie, 2008). Following the wasting disease event, eelgrass and bay scallops were absent from Nantucket Harbor for nearly 20 years (Andrews, 1990) and scallop landings reached an all-time low for the Long Island, New York fishery (MacKenzie, 2008). In Rhode Island, a tremendous harvest of scallops was described from "The Cove" at the north end of Aquidneck Island both in 1956 and again ~ 1959; intense dredging apparently destroyed the eelgrass beds in this water body and scallops were no longer found after that time (Cavanaugh[3]). Commercial harvest of the bay scallop fell precipitously in North Carolina and Chesapeake Bay (Thayer and Stuart, 1974; Orth and Moore[4]). In North Carolina, populations returned to near pre-event levels in the 1960's, but have fluctuated dramatically since that time. Moreover, North Carolina populations have exhibited a steady decline since 1995 to such a degree that the main harvest season was not opened in January 2006 and remained closed through 2009 (Burgess and Bianchi[5]; NCDMF[6,7]), although this does not appear to be the result of concomitant changes in eelgrass abundance. Bay scallop populations in Chesapeake Bay have never been restored to commercially harvestable levels since the decline of the 1930's (MacKenzie, 2008; Orth and Moore[4]).

[3]Cavanaugh, D. (deceased) Fisherman, Portsmouth, Rhode Island. Personal commun., 1972.

[4]Orth, R., and K. Moore. 1982. The biology and propagation of *Zostera marina*, in the Chesapeake Bay, Virginia. Final Rep. to U.S. Environ. Protect. Agency, Chesapeake Bay Program pursuant to Grant No. R805953, 195 p.

[5]Burgess, C., and A. Bianchi. 2004. An economic profile analysis of the commercial fishing industry in North Carolina including profiles for state-managed species. N. C. Dep. Environ. Nat. Resour., Div. Mar. Fish. Morehead City, Unpubl. rep., 228 p.

[6]N.C. Dep. Environ. Nat. Resour., Div. Mar. Fish. 2008. Stock status of important coastal fisheries in North Carolina. http://00de17f.netsolhost.com/stocks/index.html

[7]N.C. Dep. Environ. Nat. Resour., Div. Mar. Fish. 2009.Proclamation SC-1-2009. http://00de17f.netsolhost.com/procs/procs2k9/SC-1-2009.html

### Distribution

Throughout its range along the North American east coast, eelgrass is the dominant species of rooted submerged aquatic vegetation (SAV). The reported distribution of eelgrass along the east coast of the United States is from Maine to North Carolina (Fig. 6 and 7). Current estimates of eelgrass cover range from 6.75 $km^2$ in Connecticut to nearly 160 $km^2$ in Massachusetts (Table 1). When other SAV species are included, cover increases to ~500 $km^2$ (Table 1). Eelgrass populations are characterized by spatially and temporally fluctuating levels of abundance which is to be expected for a plant that is a prolific seed-setter and has a life history of only two years. Dynamic coverage has been well documented for many years (den Hartog, 1971) and is strongly associated with disturbance regime; for example, prior to the wasting disease, there is evidence that eelgrass had previously disappeared from many portions of the U.S. Atlantic coast in 1893–94, largely due to an extremely cold period, with additional losses along New England coasts in 1908 (Cottam, 1934, 1935). However, losses at that time were apparently nowhere comparable to the loss of eelgrass in the 1930's.

As coastal development accelerated in the post WWII economic boom of the United States, the depleted eelgrass populations beginning to recover from the 1930's event were faced with deteriorating water quality, increased physical disturbance from vessels and fishing, and even potential impacts from invasive species (e.g. European green crab, *Carcinus maenas;* and mute swan, *Cygnus olor*). As a result, eelgrass is at a historical low for most of the region with uncertain prospects for systematic improvement. As suggested by MacKenzie (2008) the lowered abundance of eelgrass has direct and negative implications for the scallop fisheries in the western Atlantic given this plant is historically a critical substrate for scallop.

### Maine

Information regarding the historical distribution of eelgrass in Maine prior


Figure 6.—Eelgrass distribution along the north Atlantic coast of the United States: Maine to New Jersey. Reprinted with permission from Green and Short (2003). Copyright (2003) by the UNEP World Conservation Monitoring Center. Published by the University of California Press.


Figure 7.—Eelgrass distribution along the mid Atlantic coast of the United States: Delaware to North Carolina. Reprinted with permission from Green and Short (2003). Copyright (2003) by the UNEP World Conservation Monitoring Center. Published by the University of California Press.

to the wasting disease is scarce. Cottam (1934) documented a fisherman's account that most of the eelgrass in Penobscot Bay had disappeared during 1893–94 and that many years passed before it returned. It would appear that Maine eelgrass populations suffered as elsewhere in 1908 and following the 1930's wasting disease event (Cottam, 1934). In reference to post-1930's recovery, Cottam and Munro (1954) reported that, "Though marked improvement has occurred in many places in this state during the past two or three years, eelgrass is still far below former prevalence, varying from absent or scarce to moderately abundant."Documentation of eelgrass distribution is generally lacking after the 1950's, up until the early 1990's when the Maine Department of Marine Resources (MEDMR) began mapping efforts (Barker[8]). Current eelgrass maps for Maine (utilizing data from 1992–2005) are available through the MEDMR website (MEDMR[9]). The greatest area of eelgrass is found in Casco Bay, particularly the northern region, where it appears to be at or near

[8]Barker, S. State of Maine, Department of Marine Resources, Boothbay Harbor. Personal commun., 2009

[9]MEDMR http://www.maine.gov/dmr/index.htm

Table 1.—Reported eelgrass coverage along the eastern seaboard of the United States. *dominated by *Z. marina* and *R. maritima* but also includes additional species of SAV; **includes shoal grass, *Halodule wrightii*, and *R. maritima*.

| State | Year | Area ($km^2$) | Source |
|---|---|---|---|
| Maine | 1992–2005 | 126.08 | Barker[1] |
| New Hampshire | 2006 | 8.0 | NHEP[2] |
| Massachusetts | 1995–2001 | 137.86 | Costello[3] |
| Rhode Island | 2006 | 1.88 | Bradley et al.[4] |
| Connecticut | 2006 | 6.75 | Tiner et al., 2007 |
| New York (Peconic Estuary, Long Island Sound) | 2001, 2006 | 7.20 | Tiner et al., 2007; PEP[5] |
| New Jersey (Barnegat Bay, Little Egg Harbor) | 1999 | 60.83 | Lathrop et al., 2001 |
| Delaware | 2008 | 0.01 | Anderson[6] |
| Maryland Coastal Bays | 2007 | 27.60* | Orth et al.[7] |
| Chesapeake Bay + tributaries | 2007 | 262.71* | Orth et al.[7] |
| Virginia Coastal Bays | 2007 | 16.03* | Orth et al.[7] |
| North Carolina | 1985–1992 | 500** | Ferguson et al., 1991, 1993; Ferguson and Wood[8]; NOAA[9, 10, 11] |

[1] Barker, S. State of Maine, Department of Marine Resources, Boothbay Harbor. Personal commun., 2009

[2] New Hampshire Estuaries Project (NHEP). 2006. 2006 State of the Estuaries. Durham, 32 p.

[3] Costello, C. 2007. MassDEP Eelgrass Mapping Program, 1994–2007.Unpubl. rep., State of Mass., Dep. Environ. Protect., Boston.

[4] Bradley, M., K. Raposa, and S. Tuxbury. 2007. Report on the analysis of true color aerial photography to map and inventory *Zostera marina* L. in Narragansett Bay and Block Island, Rhode Island. Environ. Data Ctr., Univ. Rhode Island, unpubl. rep., 17 p. + Eelgrass Atlas.

[5] Peconic Estuary Program (PEP), Yaphank, NY Unpubl. data

[6] Anderson, B. State of Delaware, Department of Natural Resources and Environmental Control, Dover. Personal commun., 2009.

[7] Orth, R. J., D. J. Wilcox, L. S. Nagey, A. L. Owens, J. R. Whiting, and A. K. Kenne 2008. 2007 Distribution of submerged aquatic vegetation in Chesapeake Bay and Coastal Bays.Virginia Inst. Mar. Sci., College of William and Mary, Gloucester Point. VIMS Special Scientific Report No. 151 pursuant to U.S. Environ. Prot. Agency Award #CB973013-01-0.

[8] Ferguson, R., and L. Wood. 1994. Rooted vascular beds in the Albemarle–Pamlico estuarine system. Albemarle–Pamlico Estuarine Study Report No. 94-02, 108 p.

[9] National Oceanic and Atmospheric Administration. 1994. SAV habitat from Ocracoke Inlet to Pea Island, North Carolina. NOAA, Center for Coastal Fisheries and Habitat Research, Beaufort, N.C. Unpubl. GIS data

[10] National Oceanic and Atmospheric Administration. 1992. Submerged aquatic vegetation of Bogue Sound, North Carolina 1992. NOAA, Coastal Services Center, Charleston, N.C., Unpubl. GIS data

[11] National Oceanic and Atmospheric Administration. 1990. Core Sound, North Carolina Composite SAV Data Set 1985–1990. NOAA, Coastal Services Center, Charleston, N.C., Unpubl. GIS data.

its maximum areal distribution covering much of the lower intertidal and shallow subtidal areas (Neckles et al., 2005; CBEP[10]). Commercial fishing activities contribute to localized impacts in smaller coves and embayments, particularly Maquoit Bay (Neckles et al., 2005; CBEP[10]). Additional eelgrass habitat is found in the Great Bay Estuary system, on the border of Maine and New Hampshire (see New Hampshire section below).

## New Hampshire

Eelgrass was prevalent throughout the Great Bay Estuary system (GBE) prior to a reported re-occurrence of the wasting disease in the mid 1980's which virtually eliminated the population by 1989 (Nelson, 1981; Short et al., 1986, 1993). Recovery was slow, and after reaching peak extent in 1996, eelgrass distribution in the GBE has steadily receded, accompanied by a decline in total eelgrass biomass (NHEP[11]), ostensibly due to rapidly declining water quality (nutrient loading and sedimentation; NHEP[11]; Short[12]; Beem and Short, 2009). The largest expanse of eelgrass in New Hampshire remains in Great Bay, despite a 49% decline in coverage since the 1996 peak (Short[12]). Smaller patches once scattered throughout Little Bay and deeper portions of the Piscataqua River have all but disappeared, with a combined 99% loss reported in a one-year period (2006–2007; Short[12]). Losses include an established bed of transplanted eelgrass (0.8 hectares) in the Piscataqua River from the New Hampshire Port Authority Mitigation Project (Beem and Short, 2009). The New Hampshire Estuaries Project (NHEP), administered by the University of New Hampshire, continues to survey eelgrass cover in the GBE on an annual basis. Additional information can be found at the NHEP website.[13]

## Massachusetts

Nautical charts and herbarium records from the mid 1800's through the 1920's document the prevalence of eelgrass in rivers, embayments, and nearshore coastal environments north of Boston as well as extensive eelgrass meadows throughout Boston Harbor and further south in Duxbury, Plymouth, eastern Cape Cod Bay, Waquoit Bay, and Buzzards Bay (Colarusso[14]). Eelgrass loss was documented in Massachusetts during the 1893–94 cold snap and again in 1908 (Cottam, 1934, 1935). Following the near elimination of eelgrass during the 1930's, Addy and Aylward (1944) recounted, "Eelgrass is returning in substantial amounts at many points along the Massachusetts coast and has steadily increased during the past four years, but is not as abundant anywhere as before 1930." Observations by Cottam and Munro (1954) highlight the spatial and temporal variability of the recovery process, "In some of these areas the plant is so plentiful as to impede boat travel and hinder commercial fishing. Least improvement is reported in the Gloucester–Plum Island–Newburyport section, parts of which are devoid of eelgrass."

The Massachusetts Department of Environmental Protection (MassDEP) began a comprehensive state-wide eelgrass mapping program in 1993 and interactive maps are currently available from data collected in 2001 (MassDEP[15]). Prior to this effort, quantitative mapping of the extent of eelgrass in Massachusetts is lacking, limiting efforts for longer trend analysis. However, Costa (1988) examined historic trends for Buzzards Bay although current changes (after 1980's) are not documented.

[10] Casco Bay Estuary Partnership (CBEP). 2005. 2005 State of the Bay Report. Portland, ME, 50 p.

[11] New Hampshire Estuaries Project (NHEP). 2006. 2006 State of the Estuaries. Durham, 32 p.

[12] Short, F. 2008. Eelgrass distribution in the Great Bay Estuary 2007. Final rep. of the Univ. N. H. to the N. H. Estuaries Project, Durham, 7 p.

[13] http://www.nhep.unh.edu/about/index.htm

[14] Colarusso, P. U.S. Environmental Protection Agency, Boston. Personal commun., 2009.

[15] MassDEP http://www.mass.gov/dep/

By the 1980's it appeared as if eelgrass "had saturated most available substrate" in Buzzards Bay (Costa, 1988). However, mapping efforts in the early 1990's and in 2001 indicated a renewed steady decline; over 60% of eelgrass in Buzzards Bay had been lost primarily from nutrient enrichment (Haupert and Rasmussen[16]). Similarly, nitrogen loading from coastal development has led to extensive eelgrass loss in Waquoit Bay, with 60% loss reported in a 5-year period (Short and Burdick, 1996; Hauxwell et al., 2003). Moreover, the once abundant eelgrass beds in Boston Harbor are now limited to a few locations, a result of urbanization. Despite localized losses, the coastal waters of Massachusetts support the largest quantity of eelgrass in New England.

### Rhode Island

For a detailed reconstruction of historical eelgrass locations in Narragansett Bay, consult Doherty[17] and references therein. Eelgrass is reported from 1848 herbarium records and from U.S. Coast and Geodetic Survey 1865 survey sheets (Doherty[17]). In the early 1900's, eelgrass was "harvested for fertilizer and insulation," perhaps an indication of its widespread prevalence in Narragansett Bay (Doherty[17]). Setchell (1929) observed that "*Zostera marina* occurs abundantly in the inner waters of Narragansett Bay as well as in the large protected salt ponds of southern Rhode Island." Although the wasting disease did impact a number of eelgrass populations in Narragansett Bay, significant declines are often attributed to a 1938 hurricane (Doherty[17]). In the 1950's, Rhode Island eelgrass exhibited substantial recovery following the natural disturbances of the 1930's, "In some places it is regarded as plentiful as before 1931" (Cottam and Munro, 1954).

Trend analysis conducted by the Narragansett Bay Estuary Program indicates that upper-Bay eelgrass populations have been entirely lost in the past 50–100 years due to nutrient enrichment (Bradley et al.[18]). Present-day distributions are limited to coastal ponds and isolated pockets in the lower-Bay from Prudence Island south and along the rocky eastern coast at Sakonnet Point (Bradley et al.[18]). The Rhode Island Coastal Resources Management Council (CRMC) and the University of Rhode Island's Environmental Data Center (EDC) have created a comprehensive repository for eelgrass distribution data. Interactive maps of eelgrass distribution are available through the CRMC website.[19]

### Connecticut

Historically, the distribution and abundance of eelgrass in Long Island Sound (LIS) has experienced dramatic fluctuations. A detailed description of historical distributions of eelgrass in LIS can be found in a report by the Connecticut Department of Environmental Protection and Department of Agriculture and references therein (CTDEP and CTDA[20]). In Connecticut, at the beginning of the 20th century, eelgrass was "common along the coast in bays, salt rivers, and creeks … extensively used by farmers as a fertilizer" (Graves et al., 1910). The wasting disease event virtually eliminated eelgrass from the region (Marshall, 1947) but eelgrass had shown "encouraging improvement" following the event (Cottam and Munro, 1954). By the 1970's, populations in eastern LIS had rebounded so remarkably that eelgrass was considered a nuisance. In the Niantic River Estuary, explosives were used to selectively remove eelgrass in an attempt to improve water circulation (Ludwig, 1977). However, despite a number of restoration attempts, eelgrass populations in western LIS never recovered following the wasting disease.

Throughout the 1980's and 1990's, eelgrass populations experienced a number of localized declines, most notably in the Niantic River where eelgrass became virtually non-existent (Short et al., 1988). More recently, 2006 aerial surveys conducted by the Connecticut Department of Environmental Protection and U.S. Fish and Wildlife Service inventoried 6.75 $km^2$ of eelgrass throughout eastern Long Island Sound (Connecticut waters), an increase of 1.13 $km^2$ from 2002 mapping efforts (Tiner et al., 2007). However, coverage continues to vary spatially and temporally within and among coves and small embayments. Declines are typically attributed to nutrient enrichment (Keser et al., 2003) with recovery often a result of removal of nutrient inputs (Vaudrey[21]). Following the diversion of a sewage-treatment facility wastewater outflow in 1987, portions of Mumford Cove were transformed from algal dominated communities to *Zostera marina* dominated communities within 10 years (Vaudrey[21]).

### New York

By the 1950's, although a number of Long Island locales showed "noticeable improvement" following the wasting disease, eelgrass had attained less than a quarter of its 1931 status (Cottam and Munro, 1954). In the 1960's, a number of small embayments along the southern shore of Long Island reportedly harbored extensive eelgrass beds to the point of impeding small boat traffic (Dennison et al., 1989). Brown tide events in the mid 1980's caused additional large-scale die offs of eelgrass in Long Island coastal waters (Cosper et al., 1987; Dennison et al., 1989). Only about 12% of the

[16]Haupert, C., and M. Rasmussen. 2003. 2003 State of the Bay. Coalition for Buzzards Bay, New Bedford, MA, 11 p.

[17]Doherty, A. 1995. Historical distributions of eelgrass (*Zostera marina*) in Narragansett Bay, Rhode Island. Narragansett Bay Estuary Prog. Rep. NBEP-95-121, 25 p. + app.

[18]Bradley, M., K. Raposa, and S. Tuxbury. 2007. Report on the analysis of true color aerial photography to map and inventory *Zostera marina* L. in Narragansett Bay and Block Island, Rhode Island. Environ. Data Ctr., Univ. Rhode Island, Unpubl. rep., 17 p. + Eelgrass Atlas.

[19]http://www.edc.uri.edu/Eelgrass/default.html

[20]CTDEP, and CTDA. 2007. An assessment of the impacts of commercial and recreational fishing and other activities to eelgrass in Connecticut's waters and recommendations for management. A report to the Environmental Committee of the Connecticut General Assembly pursuant to Public Act 01-115.

[21]Vaudrey, J. 2008. Establishing restoration objectives for eelgrass in Long Island Sound Part I: Review of the seagrass literature relevant to Long Island Sound. Univ. Conn. final rep. pursuant to Conn. Dep. Environ. Protect. cooperative agreement LI-97107201/CDFA#66-437. 58 p.

7.69 km$^2$ of eelgrass mapped in LIS in 2006 are in New York waters (Tiner et al., 2007). Cornell University's Cooperative Extension Eelgrass Program (CCE) monitors a number of existing eelgrass beds around Long Island and has established a number of restoration sites in Long Island Sound, Peconic Estuary, South Shore Estuary, and the Hudson–Raritan Estuary.

Prior to the wasting disease, eelgrass was prevalent in the Peconic Estuary, with an estimated coverage of 35.29 km$^2$ (CCE[22]). Eelgrass acreage from 2000 aerial surveys reported by Tiner et al. (2003) indicate an approximate 85% loss in a 70 year period. Data from the Peconic Estuary Program's Long-Term Eelgrass Monitoring Program, initiated in 1997, indicates a continual steady decline in eelgrass since the late 1990's (Pickerell and Schott[23,24]).

### New Jersey

Roughly 75% of New Jersey's SAV is found in Barnegat Bay (Lathrop et al., 2001). Following the wasting disease event, Cottam and Munro (1954) reported "excellent recovery" of eelgrass in northern Barnegat Bay but less so in the southern part of the bay. Further south, beyond the bay, "the plant is absent, or nearly so, in areas where it was once abundant" (Cottam and Munro, 1954). Continued escalation in coastal development since the mid 1970's has led to the progressive eutrophication of the Barnegat Bay–Little Egg Harbor Estuary (Kennish et al.[25]). Eelgrass acreage in the estuary peaked in the 1970's and 1980's, followed by significant declines in the 1990's and present day (Lathrop et al., 2001; Bologna et al.[26]). Recurring brown tide, phytoplankton, and macroalgae blooms have plagued the region since the mid 1990's, worsening the situation (Bologna et al., 2001; Olsen and Mahoney, 2001; Gastrich et al., 2004). In 2006, a reported 50–88% of seagrass biomass in the Barnegat Bay–Little Egg Harbor Estuary was lost, a result of accelerated macroalgal growth (Kennish et al.[25]). The Center for Remote Sensing and Spatial Analysis (CRSSA) at Rutgers University has digitized existing SAV maps dating from 1968 through 2003 to create a regional SAV time series. The interactive maps may be viewed at CRSSA's website.[27]

### Delaware

The Inland Bays of Delaware never recovered from the wasting disease of the 1930's. Cottam and Munro (1954) reported "no known stands" although restoration attempts were being made. By the late 1960's, declining water quality led to the local extinction of eelgrass in the region (Orth and Moore[28]; Sellner[29]). New environmental regulations in the 1980's, in addition to natural erosion events that led to increased flushing of the bays, greatly improved water quality in the region. Although a restoration program initiated by the Delaware Department of Natural Resources and Environmental Control (DNREC) in 1997 has resulted in approximately 0.02 km$^2$ of viable eelgrass habitat in a small region of Indian River Bay (Anderson[30]), excessive nutrient loading elsewhere prevents successful re-introduction of eelgrass (Price, 1998).

### Maryland

Eelgrass can be found from the Choptank River south to the mouth of the Chesapeake Bay and throughout the coastal bays. The extent of eelgrass habitat in Maryland's coastal bays is nowhere near its reported coverage of the 1900's. However, eelgrass coverage in the bays has increased steadily since annual monitoring began in 1986 (Wazniak et al., 2004). In contrast, many of Maryland's river estuaries, which are tributaries of Chesapeake Bay, have experienced significant declines in eelgrass primarily due to water quality issues (Stankelis et al., 2003). Large-scale restoration efforts (via seed broadcasting) initiated by the Maryland Department of Natural Resources in 2003 for the Potomac and Patuxent Rivers have met with mixed success (Busch and Golden[31]).

### Chesapeake Bay and Tributaries

Information regarding the abundance and distribution of eelgrass prior to the 1950's is lacking (Stevenson and Confer, 1978) although it appears as if eelgrass populations in the Chesapeake Bay succumbed to the cold snap experienced by New England in 1893–94 (Cottam, 1934). In 1889, eelgrass was also reported to have "almost died out in the Chesapeake area and that it were upwards of 25 years before the maximum growth had returned" (Cottam, 1934).

In the early 1900's, evidence suggests that eelgrass and other species of SAV were prevalent throughout the bay and its tributaries (Orth and Moore, 1984). Following the wasting disease event, SAV beds experienced increasing re-

[22]CCE http://counties.cce.cornell.edu/suffolk/habitat_restoration/seagrassli/index.html

[23]Pickerell, C., and S. Schott. 2004. Eelgrass trend analysis report: 1997–2002. Rep. to the Peconic Estuary Program, Yaphank, NY, 100 p.

[24]Pickerell, C., and S. Schott. 2008. Peconic Estuary Program 2006 eelgrass (*Zostera marina*) long-term monitoring program. Progress rep. to the Peconic Estuary Program, Yaphank, NY, 27 p.

[25]Kennish, M. J., S. M. Haag, and G. P. Sakowicz. 2007. Demographic investigation of submerged aquatic vegetation (SAV) in the Barnegat Bay-Little Egg Harbor Estuary with assessment of potential impacts of benthic macroalgae and brown tides. Inst. Mar. Coast. Sci., Rutgers Univ. New Brunswick, Tech. Rep. 107-15, 366 p.

[26]Bologna, P. A. X., R. Lathrop, P. D. Bowers, and K. W. Able. 2000. Assessment of the health and distribution of submerged aquatic vegetation from Little Egg Harbor, New Jersey. Inst. Mar. Coast. Sci., Rutgers Univ., Tech. Rep. #2000-11, 30 p.

[27]http://www.crssa.rutgers.edu/

[28]Orth, R, and K. Moore. 1988. Submerged aquatic vegetation in Delaware's inland bays. *In* K. Sellner (Editor), Phytoplankton, nutrients, macroalgae, and submerged aquatic vegetation in Delaware inland bays, 1985–1986, p. 86–109.Acad. Nat. Sci. final rep. to D. E. Dep. Nat. Res.

[29]Sellner, K. 1988. Phytoplankton, nutrients, macroalgae, and submerged aquatic vegetation in Delaware inland bays, 1985–1986. Acad. Nat. Sci. final rep. to D. E. Dep. Nat. Res., 140 p.

[30]Anderson, B. State of Delaware, Dep. Nat. Resour. Environ. Control, Dover. Personal commun., 2009.

[31]Busch, K., and R. Golden. 2009. Large-scale restoration of eelgrass (*Zostera marina*) in the Patuxent and Potomac Rivers, Maryland. Final rep. of the Maryland Dep. Nat. Resour. pursuant to NOAA Award #NA03NMF4570470.

covery through the 1960's (Cottam and Munro, 1954; Orth and Moore, 1984) but experienced a major setback from the effects of runoff following Tropical Storm Agnes in 1972. Again, increasing nutrient and sediment loads from development led to a precipitous baywide decline of all submerged aquatic vegetation in the 1970's (Kemp et al., 1983; Orth and Moore, 1983). Annual surveys initiated in 1984 and conducted by the Virginia Institute of Marine Science (VIMS) indicate that there continues to be considerable annual variation in all SAV coverage across the bay, with declines in some areas and recovery in others. Interactive maps can be viewed at the VIMS website.[32] Water quality issues continue to be the primary factors affecting SAV growth in Chesapeake Bay.

### Virginia Southern Coastal Bays

Following the wasting disease event and a catastrophic hurricane in 1933, eelgrass beds in this region were decimated. In the mid 1990's, the discovery of small, natural patches of eelgrass prompted an eelgrass restoration effort in the Delmarva Southern Coastal Bays of Virginia. Between 2001 and 2004, 24.2 million eelgrass seeds were broadcast by hand, resulting in the reintroduction of eelgrass to areas devoid since 1933 (Orth et al., 2006).The final, sustained acreage arising from this work remains undetermined.

### North Carolina

North Carolina represents the southern geographic boundary for eelgrass along the U.S. eastern seaboard. Although affected by the wasting disease, eelgrass populations in North Carolina were able to substantially recover and have remained relatively stable since the 1970's (Fonseca[33]). Eelgrass is found south of Oregon Inlet down through Bogue Sound. As is typical in most regions, estuaries and sounds with higher turbidity do not support eelgrass (i.e. Albemarle Sound, western Pamlico Sound). There has been no sustained effort to monitor or map seagrass state-wide until very recently, although portions of the coast were mapped in the mid 1980's and early 1990's (Ferguson et al., 1991, 1993; Ferguson and Wood[34]; NOAA[35,36,37]). The Submerged Aquatic Vegetation Mapping Partnership, facilitated by the Albemarle–Pamlico National Estuary Program (APNEP), acquired digital aerial photography from along the entire coast of North Carolina in 2007–2008. A state-wide GIS eelgrass database resulting from this imagery is in progress. For more information, consult the APNEP website.[38]

## Faunal Communities

Faunal use of eelgrass habitat is widely divergent; eelgrass fauna may include seasonal or year-round residents, may use eelgrass meadows for all or a portion of their life cycle, or may only visit the meadow for grazing purposes. The structural organization of individual eelgrass plants and eelgrass meadows as a whole allows for exploitation of a number of habitat types. Eelgrass fauna may attach directly to the leaves of the plant, bury into the sediments within a meadow, live on top of the sediment, associate with blades but remain unattached, or actively swim amongst the canopy. With the exception of some fishes, sea turtles, Brant and Canada geese, and some mollusks, few animals actually feed directly on live eelgrass plants, primarily due to the high cellulose content of the leaves, which is difficult to digest. The dominant food pathway for eelgrass itself is through the detrital food chain; its contribution to estuarine productivity is more complex and is intertwined with habitat-associated microalgae. The detritivores (crabs, shrimps, mollusks) in turn, are prey items for larger species (fish, birds).

Eelgrass meadows provide habitat, nurseries, and feeding grounds for a number of commercially, recreationally, and ecologically important species (Table 2), including the bay scallop, *Argopecten irradians*. As juveniles, bay scallops attach directly to the blades of eelgrass plants, but later drop to the sediment surface (Thayer and Stuart, 1974; Eckman, 1987; Garcia-Esquivel and Bricelj, 1993). In North Carolina, eelgrass is often the only available "hard" substrate for scallops to settle on, keeping the scallops away from predators, indicating its local importance as essential fish habitat for this species (Kirby-Smith, 1970). In addition to individual plants serving as habitat, the structure of the eelgrass meadow influences the population dynamics of the bay scallop. It has been shown that the spatial patterning of eelgrass beds can alter rates of predation on bay scallops (Irlandi et al., 1995); higher rates of predation were observed as the level of fragmentation of the bed increased (Irlandi et al., 1995). Due to the tight linkages between eelgrass and bay scallops, any change in eelgrass populations should directly affect that of the bay scallop.

## Human Threats to Eelgrass

Point and non-point source nutrient loading and sediment runoff are the primary threats to eelgrass along the Atlantic coast and are believed to be the number one cause of eelgrass decline locally. Orth and Moore (1983) reported significant declines of eelgrass in Chesapeake Bay in the late 1970's and early 1980's apparently the result of increased runoff and watershed development. Similar trends were documented by Costa (1988) for Buzzards Bay, Mass.,

[32]http://www.vims.edu/bio/sav/

[33]Fonseca, M. NOAA, Center for Coastal Fisheries and Habitat Research, Beaufort, N.C. Personal observ.

[34]Ferguson, R., and L. Wood. 1994. Rooted vascular beds in the Albemarle-Pamlico estuarine system. Albemarle-Pamlico Estuarine Study Rep. No. 94-02, 108 p.

[35]National Oceanic and Atmospheric Administration. 1994. SAV habitat from Ocracoke Inlet to Pea Island, North Carolina. NOAA, Center for Coastal Fisheries and Habitat Research, Beaufort, N.C. Unpubl. GIS data.

[36]National Oceanic and Atmospheric Administration. 1992. Submerged aquatic vegetation of Bogue Sound, North Carolina 1992. NOAA, Coastal Services Center, Charleston, N.C., Unpubl. GIS data

[37]National Oceanic and Atmospheric Administration. 1990. Core Sound, North Carolina Composite SAV Data Set 1985-1990. NOAA, Coastal Services Center, Charleston, N.C., Unpubl. GIS data

[38]http://www.apnep.org/

Table 2.—Non-inclusive list of representative commercially, recreationally, and ecologically important species using eelgrass beds along the Atlantic coast of the United States. Life history stages are represented as A = adult, J = juvenile, L = larvae, E = eggs, M = migratory. Modified from Thayer et al., 1979, 1984.

| Common Name | Scientific Name | Life Stage |
|---|---|---|
| Fish | | |
| Spotted seatrout | *Cynoscion nebulosus* | J |
| Mullet | *Mugil cephalus* | J |
| Spot | *Leiostomus xanthurus* | A, J |
| Pinfish | *Lagodon rhomboides* | A, J |
| Pigfish | *Orthopristis chrysoptera* | J |
| Gag grouper | *Mycteroperca microlepis* | J |
| Sheepshead | *Archosargus probatocephalus* | A, J |
| Thread herring | *Opisthonema oglinum* | J |
| Permit | *Trachinotus falcatus* | J |
| White grunt | *Haemulon plumieri* | J |
| Bluefish | *Pomatomus saltatrix* | A, J |
| Tautog | *Tautoga onitis* | J, E |
| Summer flounder | *Paralichthys dentatus* | A, J |
| Southern flounder | *Paralichthys lethostigma* | A, J |
| Winter flounder | *Pseudopleuronectes americanus* | J |
| Menhaden | *Brevoortia tyrannus* | A, J, L |
| Smelt | *Osmerus mordax* | M |
| Striped bass | *Morone saxatilis* | A |
| Elasmobranchs | | |
| Cownose ray | *Rhinoptera bonasus* | A, J |
| Southern stingray | *Dasyatis sabina* | A, J |
| Decapods | | |
| Brown shrimp | *Penaeus aztecus* | A, J |
| Pink shrimp | *Penaeus duorarum* | A, J |
| Blue crab | *Callinectes sapidus* | A |
| American lobster | *Homarus americanus* | J |
| Horseshoe crab | *Limulus polyphemus* | A, J |
| Mollusks | | |
| Bay scallop | *Argopecten irradians* | A, J |
| Hard clam | *Mercenaria mercenaria* | A, J |
| Soft-shell clam | *Mya arenaria* | A, J |
| Whelks | *Busycon* spp. | A, J |
| Blue mussels | *Mytilus edulis* | A, J |
| Variable Bittium | *Bittium varium* | A, J, E |
| Slipper limpet | *Crepidula convexa* | A, J, E |
| Birds | | |
| Brant goose | *Branta bernicla* | M |
| Canada goose | *Branta canadensis* | M |
| Greater scaup | *Aythya marila* | M |
| Redhead duck | *Aythya americana* | M |
| Great blue heron | *Ardea herodias* | A |
| Great egret | *Casmerodius albus* | A |
| Reptiles | | |
| Kemp's ridley sea turtle | *Lepidochelys kempii* | A, J |
| Loggerhead sea turtle | *Caretta caretta* | A, J |
| Green sea turtle | *Chelonia mydas* | A, J |

Nutrient inputs from land development, sewage treatment plants, agricultural activities, and impervious surfaces can lead to eutrophication (i.e. algal and phytoplankton blooms which reduce the amount of light penetrating to the grass bed leading to large-scale declines and/or dieoffs; Short et al., 1995; Short and Burdick, 1996). Deforestation and other disturbances to the coastal terrain (i.e. land development) deliver high amounts of sediment to inshore waters leading to increased turbidity and reduced light penetration at depth. As the coastal zone continues to be developed, these threats will not go away.

Eelgrass meadows are also vulnerable to disturbance from commercial fishing activities, especially those associated with scallop harvesting. The epibenthic dredges used to harvest bay scallops lead to dramatically decreased shoot densities and biomass of eelgrass (Fonseca et al., 1984). Bishop et al. (2005) reported a 9% loss of meadow biomass in just 10 minutes of dredge activity. Orth et al. (2002) reported on significant eelgrass impacts resulting from hard clam harvest and how careful monitoring was used to quickly modify fishing regulations to prevent further habitat loss.

## Biological Disturbance

Distribution of eelgrass is also mediated by biological disturbance (animals). Orth (1975) described substantial removal of healthy eelgrass by large numbers of cownose rays. Townsend and Fonseca (1998) showed the role of animal disturbance in the maintenance of eelgrass bed margins. Biological disturbance is also one of the primary problems facing restoration projects (Fonseca et al., 1998; see Restoring Eelgrass below).

## Restoring Eelgrass

Addy's (1947) basic logic was to match eelgrass planting and harvest site environments, and this remains a fundamental tenet in almost all seagrass planting today. Aside from early interest by Phillips (1960), almost 30 years elapsed before serious attention to planting seagrass developed. It was not until the 1970's that documents again began to emerge presenting seagrass planting in a guideline format, culminating in a national guidelines document (Fonseca et al., 1998). But even though suitable planting methods have long existed, the track record for successful mitigation of impacts to eelgrass beds remains variable (see review by Phillips, 1982).

Much emphasis was placed on technique development in the late 1970's and early 1980's, but relatively little attention was given to developing a management framework within which these techniques could be effectively implemented. As a result, most seagrass mitigation projects have failed to achieve even the goal of 1:1 habitat replacement (i.e. offset a net loss of seagrass habitat). Nonetheless, eelgrass beds have often been successfully planted and have come to perform much as naturally-propagated beds (see review by Fonseca et al., 1998).

Of all the North American seagrasses, eelgrass has a growth rate and strategy that makes it especially conducive to restoration. As mentioned earlier, eelgrass plants migrate across the seafloor and are morphologically plastic which provides an adaptive advantage in that

they have some capacity to locate more favorable conditions. They are also prolific in their seed production, giving them another advantage in that they can disperse broadly. Finally, as each shoot is terminal on a rhizome, each shoot is a viable contributor to both daughter ramets (new members of the population) and seeds (in their second year when in their perennial form). Unlike many other seagrasses that put down stationary shoots that do not subsequently add to population growth (with the exception of infrequent branching for some species) and are thus not useful in vegetative transplants, eelgrass shoots are all viable transplanting units and thus fewer shoots are needed for harvest and installation. For a full review of eelgrass and other seagrass restoration, see Fonseca et al. (1998).

While methodological innovations continue, the limitations to restoring this crucial national resource are rarely technical (there are many viable techniques), but instead lay in the utilization of extant knowledge. Recent advances in eelgrass seeding and whole plant restoration technologies (see review in Fonseca et al., 1998) demonstrate the ongoing decline of methodological limitations. Problems tend to emerge in the application of this knowledge; for example, the expectations of eelgrass restoration are grossly unrealistic being held as they are to standards often higher than agricultural crops despite the huge disparity in our knowledge base and economic subsidy among these practices. Aside from unrealistic expectations of success, chief among the problems facing resource managers today is the tendency for project applicants to select planting areas where there is no prior history of their existence (unless of course the site was created for the purposes of planting seagrass). The chronic absence of seagrass from a site, especially when there are propagule sources nearby, usually indicates that the site cannot consistently support seagrasses. Ensuring sufficient light, moderate nutrient loads, and protecting plantings from disturbance constitute the other major caveats for developing a persistent eelgrass bed.

## Conclusions

Eelgrass has been shown to be a critical part of the bay scallop life cycle, providing substrate for settlement and subsequent shelter and feeding (Thayer and Stuart, 1974; Eckman, 1987; Garcia-Esquivel and Bricelj, 1993; Irlandi et al., 1995). Thus, bay scallop abundance and the success of the fishery appear to be inextricably linked to the health of eelgrass habitat. However, eelgrass in the western Atlantic is almost certainly at an historic low since the wasting disease event of the 1930's, a result of human development of the coastal zone. We conclude that the reduced distribution of eelgrass, together with periodic heavy fishing pressure on scallops (MacKenzie, 2008) combine to produce the current marginal health of that fishery. Moreover, natural fluctuations in both eelgrass distribution and the erratic nature of the bay scallop population cycle (MacKenzie, 2008) may further limit scallop population persistence through habitat fragmentation and scallop recruitment limitation which all point to a fishery with profound challenges for survival.

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## Literature Cited

Addy, C. E. 1947. Eel grass planting guide. Maryland Conserv. 24:16–17.

________ and D. A. Aylward. 1944. Status of eelgrass in Massachusetts during 1943. J. Wildl. Manage. 8(4):269–275.

Andrews, J. C. 1990. Fishing around Nantucket. The Maria Mitchell Assoc. Nantucket, Mass., 76 p.

Beem, N. T., and F. T. Short. 2009. Subtidal eelgrass declines in the Great Bay estuary, New Hampshire and Maine, USA. Estuaries Coasts 32:202–205.

Bintz, J. C., S. W. Nixon, B. A. Buckely, and S. L. Granger. 2003. Impacts of temperature and nutrients on coastal lagoon plant communities. Estuaries 26(3):765–776.

Bishop, M. J., C. H. Peterson, H. C. Summerson, and D. Gaskill. 2005. Effects of harvesting methods on sustainability of a bay scallop fishery: dredging uproots seagrass and displaces recruits. Fish. Bull. 103:712–719.

Bologna, P., A. Wilbur, and K. Able. 2001. Reproduction, population structure, and recruitment limitation in a bay scallop (*Argopecten irradians* Lamarck) population from New Jersey, USA. J. Shellfish Res. 20(1):89–96.

Burdick, D. M., F. T. Short, and J. Wolf. 1993. An index to assess and monitor the progression of wasting disease in eelgrass *Zostera marina*. Mar. Ecol. Prog. Ser. 94:83–90.

Cosper, E. M., W. C. Dennison, E. J. Carpenter, V. M. Bricelj, J. G. Mitchell, S. H. Kuenster, D. Colflesh, and M. Dewey. 1987. Recurrent and persistent brown tide blooms perturb coastal marine ecosystem. Estuaries 10(4): 284–290.

Costa, J. 1988. Eelgrass in Buzzards Bay: distribution, production, and historical changes in abundance. U.S. Environ. Protect. Agency Rep. EPA 503/4-88-002, Wash. D.C., 204 p.

Cottam, C. 1934. Past periods of eelgrass scarcity. Rhodora 36(427):261–264.

________. 1935. Further notes on past periods of eelgrass scarcity. Rhodora 37(440):269–271.

________ and D. A. Munro. 1954. Eelgrass status and environmental relations. J. Wildl. Manage. 18(4):449–460.

den Hartog, C. 1971. The dynamic aspect in the ecology of seagrass communities. Thalassia Jugosl. 7:101–112.

Dennison, W. C. 1987. Effects of light on seagrass photosynthesis, growth and depth distribution. Aquat. Bot. 27(1):15–26.

________, R. J. Orth, K. A. Moore, J. C. Stevenson, V. Carter, S. Kollar, P. Bergstrom, and R. A. Batiuk. 1993. Assessing water quality with submersed aquatic vegetation. Bioscience 43(2):86–94.

________, G. J. Marshall, and C. Wigand. 1989. Effect of "brown tide" shading on eelgrass (*Zostera marina* L.) distributions. *In* E. M. Cosper, V. M. Bricelj, and E. J. Carpenter (Editors), Novel phytoplankton blooms: Causes and impacts of recurrent brown tides and other unusual blooms, p. 675–692. Springer-Verlag, Berlin.

Eckman, J. E. 1987. The roll of hydrodynamics in recruitment, growth, and survival of *Argopecten irradians* (L.) and *Anomie simplex* (D'Orbigny) within eelgrass meadows. J. Exp. Mar. Biol. Ecol. 106(2):165–191.

Evans, A. S., K. L. Webb, and P. A. Penhale. 1986. Photosynthetic temperature acclimation in two coexisting seagrasses, *Zostera marina* L.and *Ruppia maritima* L. Aquat. Bot. 24(2):185–197.

Ferguson, R. L., and K. Korfmacher. 1997. Remote sensing and GIS analysis of seagrass meadows in North Carolina, USA. Aquat. Bot. 58(3–4):241–258.

________, L. L. Wood, and D. B. Graham. 1993. Monitoring spatial change in seagrass habitat with aerial photography. Photogram. Eng. Rem. Sens. 59(6):1033–1038.

________, ________, and B. T. Pawlak. 1991. SAV habitat from Drum Inlet to Ocracoke Inlet, North Carolina. NOAA Coastal Ocean Program Submerged Aquatic Vegetation Study. U.S. Dep. Commer., NOAA, NMFS

Beaufort Lab., Beaufort, N.C. (3- × 4-foot chart with text and illust.)
Fonseca, M. S., and S. S. Bell. 1998. Influence of physical setting on seagrass landscapes near Beaufort, North Carolina, USA. Mar. Ecol. Prog. Ser. 171:109–121.
________ and J. A. Cahalan. 1992. A preliminary evaluation of wave attenuation by four species of seagrass. Estuarine Coastal Shelf Sci. 35(6):565–576.
________ and J. S. Fisher. 1986. A comparison of canopy friction and sediment movement between four species of seagrass with reference to their ecology and restoration. Mar. Ecol. Prog. Ser. 29:15–22.
________ , W. J. Kenworthy, and G. W. Thayer. 1998. Guidelines for the conservation and restoration of seagrasses in the United States and adjacent waters. NOAA Coastal Ocean Prog. Decision Analysis Ser. No. 12. NOAA Coastal Ocean Off., Silver Spring, Md., 222 p.
________ , G. W. Thayer, and A. J. Chester. 1984. Impact of scallop harvesting on eelgrass (*Zostera marina*) meadows: implications for management. N. Am. J. Fish. Manage. 4(3):286–293.
________ , P. E. Whitfield, N. M. Kelly, and S. S. Bell. 2002. Modeling seagrass landscape pattern and associated ecological attributes. Ecol. Appl. 12(1):218–237.
________ , J. C. Zieman, G. W. Thayer, and J. S. Fisher. 1983. The role of current velocity in structuring eelgrass (*Zostera marina* L.) meadows. Estuarine Coastal Shelf. Sci. 17(4):367–380.
Gallegos, C. L. 1994. Refining habitat requirements of submersed aquatic vegetation: role of optical models. Estuaries 17(1):198–209.
Garcia-Esquivel, Z., and V. M. Bricelj. 1993. Ontogenetic changes in microhabitat distribution of juvenile bay scallops, *Argopecten irradians irradians* (L.), in eelgrass beds, and their potential significance to early recruitment. Biol. Bull. 185(1):42–55.
Gastrich, M. D., J. A. Leigh-Bell, C. J. Gobler, O. R. Anderson, S. W. Wilhelm, and M. Bryan. 2004. Viruses as potential regulators of regional brown-tide blooms caused by the alga, *Aureococcus anophagefferens*. Estuaries 27(1):112–119.
Green, E. P., and F. T. Short. 2003. World Atlas of Seagrass. Prepared by the UNEP World Conservation Monitoring Centre. Univ. Calif. Press, Berkley, 298 p.
Graves, C. B., E. H. Eames, C. H. Bissel, L. Andrews, E. B. Harger, and C. A. Weatherby. 1910. Catalogue of the flowering plants and ferns of Connecticut. Conn. Geol. Nat. Hist. Survey Bull. No. 14, Hartford, Conn., 569 p.
Grizzle, R. E., F. T. Short, C. R. Newell, H. Hoven, and L. Kindblom. 1996. Hydrodynamically induced synchronous waving of seagrasses, "monami"and its possible effects on larval mussel settlement. J. Exp. Mar. Bio. Ecol. 206(12):165–177.
Harwell, M. C., and R. J. Orth. 2002. Long-distance dispersal potential in a marine macrophyte. Ecology 83(12):3319–3330.
Hauxwell, J., J. Cebrian, and I. Valiela. 2003. Eelgrass *Zostera marina* loss in temperate estuaries: relationship to land-derived nitrogen loads and effect of light limitation imposed by algae. Mar. Ecol. Prog. Ser. 247:59–73.
Irlandi, E. A., W. G. Ambrose, Jr., and B. A. Orlando. 1995. Landscape ecology and the marine environment: how spatial configuration of seagrass habitat influences growth and survival of the bay scallop. Oikos 72(3):307–313.
Kemp, M., R. Batiuk, R. Bartleson, P. Bergstrom, V. Carter, C. L. Gallegos, W. Hunley, L. Karrh, E. W. Koch, J. M. Landwehr, K. A. Moore, L. Murray, M. Naylor, N. B. Rybicki, J. C. Stevenson, and D. J. Wilcox. 2004. Habitat requirements for submerged aquatic vegetation in Chesapeake Bay: water quality, light regime, and physical-chemical factors. Estuaries 27(3):363–377.
________ , W. R. Boynton, J. C. Stevenson, R. R. Twilley, and J. C. Means. 1983. The decline of submerged vascular plants in upper Chesapeake Bay: summary of results concerning possible causes. Mar. Technol. Soc. J. 17:78–89.
Keser, M., J. T. Swenarton, J. M. Vozarik, and J. F. Foertch. 2003. Decline in eelgrass (*Zostera marina* L.) in Long Island Sound near Millstone Point, Connecticut (USA) unrelated to thermal input. J. Sea Res. 49(1):11–26.
Kirby-Smith, W. W. 1970. Growth of the scallops, *Argopecten irradians concentricus* (Say) and *Argopecten gibbus* (Linné), as influenced by food and temperature. Ph.D. Dissertation, Duke University, Durham, N.C., 126 p.
Koch, E. W. 2001. Beyond light: physical geological, and geochemical parameters as possible submersed aquatic vegetation habitat requirements. Estuaries 24(1):1–17.
Lathrop, R., R. Styles, S. Seitzinger, and J. Bognar. 2001. Use of GIS mapping and modeling approaches to examine the spatial distribution of seagrasses in Barnegat Bay, New Jersey. Estuaries 24(6):904–916.
Ludwig, M. 1977. Environmental assessment of the use of explosives for selective removal of eelgrass (*Zostera marina*). *In* G. A. Young (Editor), Proceedings of the Second Conference on the Environmental Effects of Explosives and Explosions. p. 63–68. Naval Surface Weapons Center, Silver Spring, Md.
MacKenzie, C. L., Jr. 2008. The bay scallop, *Argopecten irradians*, Massachusetts through North Carolina: its biology and the history of its habitats and fisheries. Mar. Fish. Rev. 70(3–4):6–79.
Marsh, J. A., W. C. Dennison, and R. S. Alberte. 1986. Effects of temperature on photosynthesis and respiration in eelgrass (*Zostera marina* L.). J. Exp. Mar. Biol. Ecol. 101(3):257–267.
Marshall, N. 1947. An abundance of bay scallops in the absence of eelgrass. Ecology 28(3):321–322.
McRoy, C. P., and R. J. Barsdate. 1970. Phosphate adsorption in eelgrass. Limnol. Oceanogr. 15(1):6–13.
________ , R. J. Barsdate, and M. Nebert. 1972. Phosphorous cycling in an eelgrass (*Zostera marina* L.) ecosystem. Limnol. Oceanogr. 17(1):58–67.
Mills, K., and M. S. Fonseca. 2003. Mortality and productivity of eelgrass *Zostera marina* under conditions of experimental burial with two sediment types. Mar. Ecol. Prog. Ser. 255:127–134.
Moore, K. A., R. L. Wetzel, and R. J. Orth. 1997. Seasonal pulses of turbidity and their relations to eelgrass (*Zostera marina* L.) survival in an estuary. J. Exp. Mar. Biol. Ecol. 215(1):115–134.
Muehlstein, L. K. 1989. Perspectives on the wasting disease of eelgrass *Zostera marina*. Dis. Aquat. Org. 7:211–221.
________ , D. Porter, and F. T. Short. 1988. *Labyrinthula* sp., a marine slime mold producing the symptoms of wasting disease in eelgrass, *Zostera marina*. Mar. Biol. 99:465–472.
________ , ________ , and ________ . 1991. *Labyrinthula zosterae sp. Nov.*, the causative agent of wasting disease of eelgrass, *Zostera marina*. Mycologia 83(2):180–191.
Neckles, H. A., F. T. Short, S. Barker, and B. S. Kopp. 2005. Disturbance of eelgrass *Zostera marina* by commercial mussel *Mytilus edulis* harvesting in Maine: dragging impacts and habitat recovery. Mar. Ecol. Prog. Ser. 285:57–73.
Nelson, J. I. 1981. Inventory of natural resources of Great Bay estuarine system. Vol. I. N.H. Fish and Game Dep., Concord, 254 p.
Olsen, P. S., and J. B. Mahoney. 2001. Phytoplankton in the Barnegat Bay–Little Egg Harbor estuarine system: species composition and picoplankton bloom development. J. Coast. Res. 32(SI):115–143.
Orth, R. J. 1975. Destruction of eelgrass, *Zostera marina*, by the cownose ray, *Rhinoptera bonasus*, in the Chesapeake Bay. Chesapeake Sci. 16(3):205–208.
________ and K. A. Moore. 1983. Chesapeake Bay: An unprecedented decline in submerged aquatic vegetation. Science 222:51–53.
________ and ________ . 1984. Distribution and abundance of submerged aquatic vegetation in Chesapeake Bayan historical perspective. Estuaries 7(4):531–540.
________ , J. R. Fishman, D. J. Wilcox, and K. A. Moore. 2002. Identification and management of fishing gear impacts in a recovering seagrass system in the coastal bays of the Delmarva peninsula, USA. J. Coast. Res. 37(SI):111–129.
________ , M. L. Luckenbach, S. R. Marion, K. A. Moore, and D. J. Wilcox. 2006. Seagrass recovery in the Delmarva coastal bays, USA. Aquat. Bot. 84(1):26–36.
Penhale, P. A. 1977. Macrophyte-epiphyte biomass and productivity in an eelgrass (*Zostera marina* L.) community. J. Exp. Mar. Biol. Ecol. 26(2):211–224.
Phillips, R. C. 1960. Observations on the ecology and distribution of the Florida seagrasses. Fla. State Board Conserv. Prof. Papers Ser., No. 2, 72 p.
________ . 1982. Seagrass meadows. *In* R. R. Lewis (Editor), Creation and restoration of coastal plant communities, p. 173–202. CRC Press, Boca Raton, Fla.
________ and E. G. Meñez. 1988. Seagrasses. Smithsonian Contrib. Mar. Sci. 34:1–104.
Price, K. S. 1998. A framework for a Delaware Inland Bays environmental classification. Environ. Monit. Assess. 51(1–2):285–298.
Rasmussen, E. 1977. The wasting disease of eelgrass (*Zostera marina*) and its effects on environmental factors and fauna. *In* C. P. McRoy and C. Helfferich (Editors), Seagrass ecosystems: a scientific perspective, p. 1–52. Marcel Dekker, N.Y.
Setchell, W. A. 1929. Morphological and phenological notes on *Zostera marina* L. Calif. Publ. Bot. 14(19):389–452.
Short, F. T. 1983a. The response of interstitial ammonium in eelgrass (*Zostera marina* L.) beds to environmental perturbations. J. Exp. Mar. Biol. Ecol. 68(2):195–208.
________ . 1983b. The seagrass *Zostera marina* L.: plant morphology and bed structure in relation to sediment ammonium in Izembek Lagoon, Alaska. Aquat. Bot. 16(2):149–161.

________ . 1987. Effects of sediment nutrients on seagrasses: literature review and mesocosm experiment. Aquat. Bot. 27(1):41–57.

________ and D. M. Burdick. 1996. Quantifying eelgrass habitat loss in relation to housing development and nitrogen loading in Waquoit Bay, Massachusetts. Estuaries 19(3):730–739.

________ and C. A. Short. 2003. The seagrasses of the western North Atlantic. *In* E. P. Green and F. T. Short (Editors), World Atlas of Seagrasses, p. 207–215. Univ. Calif. Press, Berkley.

________ , D. M. Burdick, and J. E. Kaldy. 1995. Mesocosm experiments quantify the effects of eutrophication on eelgrass, *Zostera marina* L. Limnol. Oceanogr. 40(4):740–749.

________ , ________ , J. S. Wolf, and G. E. Jones. 1993. Eelgrass in estuarine research reserves along the east coast, USA. Part I: Declines from pollution and disease. U.S. Dep. Commer, NOAA Coastal Ocean Prog. Publ., 83 p.

________ , B. W. Ibelings, and C. den Hartog. 1988. Comparisons of a current eelgrass disease to the wasting disease in the 1930's. Aquat. Bot. 30(4):295–304.

________ , A. C. Mathieson, and J. I. Nelson. 1986. Recurrence of the eelgrass wasting disease at the border of New Hampshire and Maine, USA. Mar. Ecol. Prog. Ser. 29:89–92.

________ , L. K. Muehlstein, and D. Porter. 1987. Eelgrass wasting disease: cause and recurrence of a marine epidemic. Biol. Bull. 173(2):557–562.

Stankelis, R. M., M. D. Naylor, and W. R. Boynton. 2003. Submerged aquatic vegetation in the mesohaline region of the Patuxent Estuary: past, present, and future status. Estuaries 26(2):186–195.

Stevenson, J. C., and N. M. Confer. 1978. Summary of available information on Chesapeake Bay submerged aquatic vegetation. U.S. Fish and Wildl. Serv. FWS/OBS 78/66, Wash. D.C., 335 p.

Thayer, G. W., and H. H. Stuart. 1974. The bay scallop makes its home of seagrass. Mar. Fish. Rev. 36(7):27–30.

________ , W. J. Kenworthy, and M. S. Fonseca. 1984. The ecology of eelgrass meadows of the Atlantic coast: a community profile. U. S. Fish Wildl. Serv. FWS/OBS-84/02, Wash. D.C., 147 p.

________ , H. H. Stuart, W. J. Kenworthy, J. F. Ustach, and A. B. Hall. 1979. Habitat values of salt marshes, mangroves, and seagrasses for aquatic organisms. *In* P. E. Greeson, J. R. Clark, and J. E. Clark (Editors), Wetland functions and values: the state of our understanding, p. 235–247. Am. Water Res. Assoc., Minneapolis, Minn.

Tiner, R., H. Bergquist, T. Halavik, and A. MacLachlan. 2003. Eelgrass Survey for Eastern Long Island Sound, Connecticut and New York. Natl. Wetlands Inventory Prog. Rep. U.S. Fish Wildl. Serv., Hadley, Mass., 14 p. + app.

________ , ________ , ________ , and ________ . 2007. 2006 Eelgrass Survey for Eastern Long Island Sound, Connecticut and New York. Natl. Wetlands Inventory Prog. Rep., U.S. Fish Wildl. Serv., Hadley, Mass., 24 p. + app.

Townsend, E., and M. S. Fonseca. 1998. The influence of bioturbation on seagrass landscape patterns. Mar. Ecol. Prog. Ser. 169:123–132.

Tutin, T. G. 1938. The autecology of *Zostera marina* in relation to its wasting disease. New Phytol. 37(1):50–71.

Wazniak, C., L. Karrh, T. Parham, M. Naylor, M. Hall, T. Carruthers, and R. Orth. 2004. Seagrass abundance and habitat criteria in the Maryland coastal bays. *In* C. E. Wazniak and M. R. Hall (Editors), Maryland's coastal bays: Ecosystem health assessment 2004, p. 6.1–6.17. Maryland Dep. Nat. Resour., Annapolis.

Zimmerman, R. C., R. D. Smith, and R. A. Alberte. 1989. Thermal acclimation and whole-plant carbon balance in *Zostera marina* (eelgrass). J. Exp. Mar. Biol. Ecol. 130(2):93–109.

# Geomorphological Evolution of Estuaries: The Dynamic Basis for Morpho-Sedimentary Units in Selected Estuaries in the Northeastern United States

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## Background

The basic concept of an estuary is that it is an aquatic system located at the land-sea interface, and it is a transition feature, extending from freshwater to marine environments. Day (1981) offers a more detailed explanatory description of the estuarine ecotone that allows for intermittent connection to the ocean and adds aspects of freshwater flow. Kennish (2000) amplifies the variety of descriptors to include classifications based on physiography, hydrography, salinity and tidal characteristics, sedimentation, as well as ecosystem energetics.

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*ABSTRACT—The coastal geomorphological processes of alongshore transport and tidal currents are interacting with the attendant influences of sea-level rise and sediment supply to generate morpho-sedimentary units in selected estuarine systems. Constrained by the conditions promoted by microtidal situations in barrier island settings, vectors of sediment transport have established spatial sequences of morphologies and sediment types that are components of shellfish habitats. Greater depth and decreasing grain-size toward the mainland are common characteristics in five northeastern U.S. estuarine systems. The patterns are repeated at various scales among the lagoon-type estuaries as well as within the estuarine settings to establish geospatial associations of geomorphology and habitat.*

This paper is not an attempt to define and describe all estuaries, but it focuses on five estuaries in the northeastern portion of the United States (Fig. 1). In so doing, it identifies the geomorphological setting of these estuaries and provides context to the sedimentological characteristics of a few types of shellfish habitat. It also establishes spatial associations of sediment types and provides explanatory descriptions of grain-size distributions that are often associated with shellfish abundance (MacKenzie et al., 2006).

## Geomorphological Basis

The physical features that occur at the marine margin of the continents and islands are largely the products of the last few thousand years, the Late Holocene, when the rising ocean inundated the margins of the land masses and created the present-day matrix of coastal and estuarine systems. Whereas many of


Figure 1.—The five estuaries presented in this paper.

the estuarine settings are derived from the drowned topography and pre-existing forms (Isla, 1995), some aspects of the estuarine settings are produced by the ambient processes and available sediments following the Late Holocene sea-level position (Perillo, 1995; Roman et al., 2000; FitzGerald and Knight, 2005).

The present sea level position is associated with the most recent and relatively slow rise of several meters (including water rising and land subsiding) during the last several thousand years after millennia of very rapid rise. Although there is local variation, a similar regional pattern of relative sea-level rise in the Northeast is in agreement with the trends reported in coastal Massachusetts and Connecticut by Donnelly (2006), a relative rise of about 2.6 m in the past 3,300 years. The recent inundation includes a rate of 0.8 ±0.25 mm/yr during 3300–1000 YBP, and a rate of 0.52 ±0.62 mm/yr from 1000 YBP to 150–500 years ago. However, it must be pointed out that relative sea-level rise has increased substantially in the past several centuries to 2–4 mm/yr (Bindoff et al., 2007). Importantly, the recent (past 3,300 years) slow rate of sea-level rise was accompanied by sediment accumulation in the form of barrier islands and wetland expansion at the coast that contributed to the geomorphological characteristics of the estuaries (Walker and Coleman, 1987).

Several studies have created geomorphological groupings of estuaries. Kennish (1986) has summarized a wide range of estuarine literature to produce a classification that consists of four broad genetic associations: 1) drowned river valleys; 2) lagoon-type, bar-built; 3) fjord-type; and 4) tectonically produced. That classification includes the major groupings but lacks details of the geomorphological products. Earlier, Davies (1964) approached estuaries as groupings within a climatic and geographical association, describing estuarine form related to glacial processes at one climatic extreme and to coralline processes at the other extreme, creating a primary classification very much like the more recent effort by Kennish. However, Davies further reviewed the active geomorphological processes (waves, tidal range, tidal currents, storms) associated with estuaries and suggested that tidal range was a major variable in the development of morpho-sedimentological characteristics within estuarine settings. He identified the concept of micro-, meso-, and macro-tidal morphologies later amplified by Hayes (1975, 1980) as a basis for discriminating groupings of process-response characteristics (processes acting upon sediments to produce morphologies) in coastal settings.

Essentially, estuarine coastal areas with low tidal ranges will tend to have impressive tidal deltas and considerable sedimentation driven through the functioning inlets to create flood-tide or ebb-tide dominated deltas with a myriad of channels and delta lobes (Knight and FitzGerald, 2005). As tidal range increases, the dominance of the tidally-created landforms tends to decrease and fluvial forms at the inland margin of the estuary become more significant. At the extreme, the macrotidal estuary has a broad mouth open to the sea. Waves and sediment supply are important to the microtidal condition because the coastwise barrier and the tidal deltas are composed of sand delivered along the shore face. However, rather than inland transfers along the entire seaward margin of the estuary (as in the high tidal range coasts), the transfers in the microtidal settings are restricted to the presence of inlets and the growth of tidal deltas at those sites.

Implicit in both Davies (1964) and Hayes (1975) is the availability of sediment to create the morpho-sedimentological units. Sediment becomes an additional variable because the coastal system is transporting material through space across time. Therefore, some aspects of the geomorphological evolution of form may never reach full development because of a sediment limitation, or some aspects may be in an accumulating or eroding mode because of vectors of sediment delivery. In site-specific examples, the products of a process-response association are often constrained by the quantity and quality of sediments available (Cooper, 2001). The variety of input sources determines the size and mineralogy of the sediments delivered to the estuaries, and therefore, it is common to find a wide range of sediment sizes in an estuarine environment. Estuarine sediments may range in size from gravel (>2 mm), to silt (<1/16 mm), but most common grain sizes are found in the sand class ranging in size among very coarse sand (2–1 mm); coarse sand (1–1/2 mm); medium sand (1/2–1/4 mm); fine sand (1/4–1/8 mm); and very fine sand (1/8–1/16 mm).

The following discussion and descriptions apply the concepts of coastal geomorphological associations to the evolution of five specific estuaries in the northeastern portion of the United States and offer some insights to the distribution of physical characteristics within these sites. By extension, the pattern of morphologies and sediment types interfaces with flows, bathymetry, and salinity gradients to influence shellfish distributions (Hunt, 2005; Mann et al., 2005).

### Barnegat Bay

The Barnegat Bay embayment is a shore parallel estuary with an area of 155 km$^2$ and one direct inlet. It has a coastal length of about 39 km and a width that varies from less than 1.0 km at its northern portion to about 7 km opposite Barnegat Inlet (Fig. 2). The dominant tides are microtidal, varying from a range of about 0.6 m spring tide to 0.3 neap tide at the inlet and decreasing away from the inlet (Guo et al., 1997). The estuary is shallowest at its eastern margin, adjacent to the barrier, and deepest (maximum of 7 m) toward the contact with the continent (Kennish, 2001). The morpho-sedimentary units within the estuary are related to the geomorphological evolution of the barrier spit as it migrated inland and extended southerly (Psuty, 2004). Availability of sediment has been a constraint. Some of the limitation is related to the source area. According to McMaster (1954), the alongshore transport supplying the barrier island seaward of Barnegat Bay is limited to erosion of the Pleistocene headland north of the bay and a very limited supply of sediment from offshore.

The result of that limitation is a narrow barrier and a very restricted flood-tide delta and overwash contribution as the barrier was extending southward. Further, by the time the barrier equilibrated in position relative to sea-level rise, the inlet was near the southern margin of the estuary.

Independent of the exact causal situation, the present geomorphological association is a variation in the morpho-sedimentary units along the long axis of the Barnegat estuary (Fig. 2, 3). The dominant sedimentary feature is the broad zone of medium sand that forms a 2–3 km wide shelf extending westerly from the barrier spit into the bay. The shelf increases to 4–5 km in width nearer Barnegat inlet and sediment sizes shift toward coarse sand. There are two morpho-sedimentary trends evidenced. One is the increasing width of the medium-sand shelf with a depth of up to 2 m from north to south. The other is the grain size gradient that is coarser on the ocean side of the estuary and finer toward the continent; this characteristic also co-varies with depth in the estuary. This morphological assemblage is consistent with the persistence of a major inlet in the southern portion of the estuary and the accumulation of sediment in a flood-tide delta process-response relationship. It is also in agreement with the importance of tidal currents in the generation of morpho-sedimentary units in microtidal locations (Davies, 1964; Hayes, 1980).

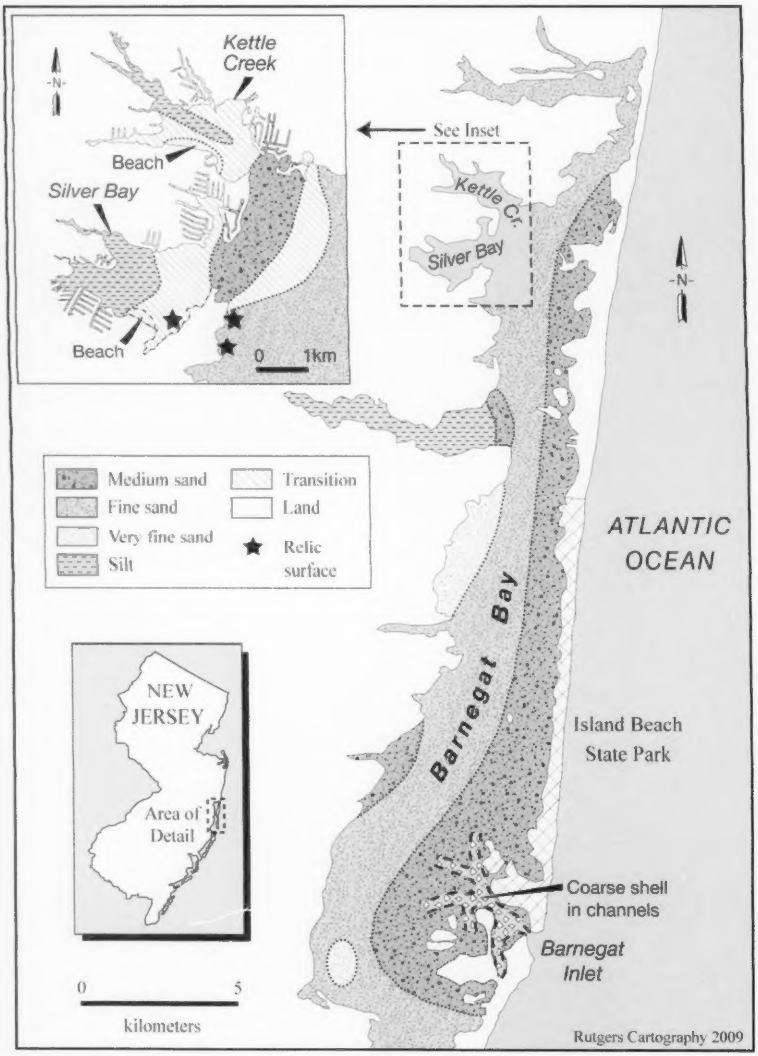


Figure 2.—Distribution of morpho-sedimentary units in Barnegat Bay; detailed distribution of morpho-sedimentary units in the Silver Bay–Kettle Creek micro-estuaries.

The major geomorphological feature is the extensive flood-tide delta at the present location of Barnegat Inlet and its variety of forms and sediment types. The inlet has been artificially stabilized since 1939 and the flood tide delta had been expanding into the southern bay prior to stabilization (Kennish, 2000). Although the delta is composed largely of medium sand, the deeper tidal channels in the delta are lined with coarse shell debris and some gravel, creating lineations and habitats cutting across the general morpho-sedimentary units. Former flood-tide delta forms compose the broad shelf along the estuarine margin of the barrier spit, and subsequent re-working of the tidal delta deposits has altered most of their channel morphologies. Thus, whereas there may be ancestral lobate sedimentary projections into the bay associated with former inlets or washover features, there is little variation in the deltaic morphology or sediment type at this time, and little variation in shellfish habitat.

The northern and inland part of the Barnegat Bay has a repetitive suite of morpho-sedimentary units that is related to tidal flows in the minor drainage channels emanating from the mainland. Detailed analysis of bottom sediments in the Kettle Creek–Silver Bay area identify the local interaction of tidal currents and wave action that create sandy barriers across the mouths of each of the small drainage channels (Fig. 2, inset). The pattern consists of a well-sorted, medium sand accumulation that extends as a shallow bar across the

mouth of the channel. Tidal flows and local wave action have concentrated the coarser sands at these locations, with finer sediments both inland and bayward of the bar. The association of sediment type and morphology is well-displayed in the bivariate plot of grain-size versus a measure of sorting (expressed as standard deviation in phi units) for the complex situation found at the Kettle Creek–Silver Bay site (Fig. 4).

The points on the plot are sediment sample sites and they cluster in the following groups: 1) the sand bar at the mouth of the channels is well-sorted medium sand; 2) the sediments at the inland portions of the micro-estuaries are composed of silts with poorer sorting than the bar; 3) there is a narrow beach at the southern margin of the channels that is well-sorted very fine sand; 4) there is a transition zone to either side of the bar environment that incorporates fluvial silts, the mean grain size is between the two major clusters and has poorer sorting; and 5) some of the bottom in these micro-estuaries (and elsewhere in the larger estuary) lacks any new sediment accumulation and consists of an old oxidized surface with gravels and pebbles (with a large mean grain size and very poor sorting), this is a kind of relic topography that is not related to the modern coastal or estuarine processes or sediment supply.

Portions of the continental margins of the estuary have narrow beach deposits that extend into the adjacent water and create spatially-limited bottom types because of the exposure to ambient wave conditions and available sediments. They form isolated shore-parallel bands of well-sorted medium-to-fine sand bounded by finer sediments.

Importantly, the juxtaposition of sediments and morphologies present in Barnegat Bay represents associations of hydrographies and flows that create shellfish habitats and they may be re-

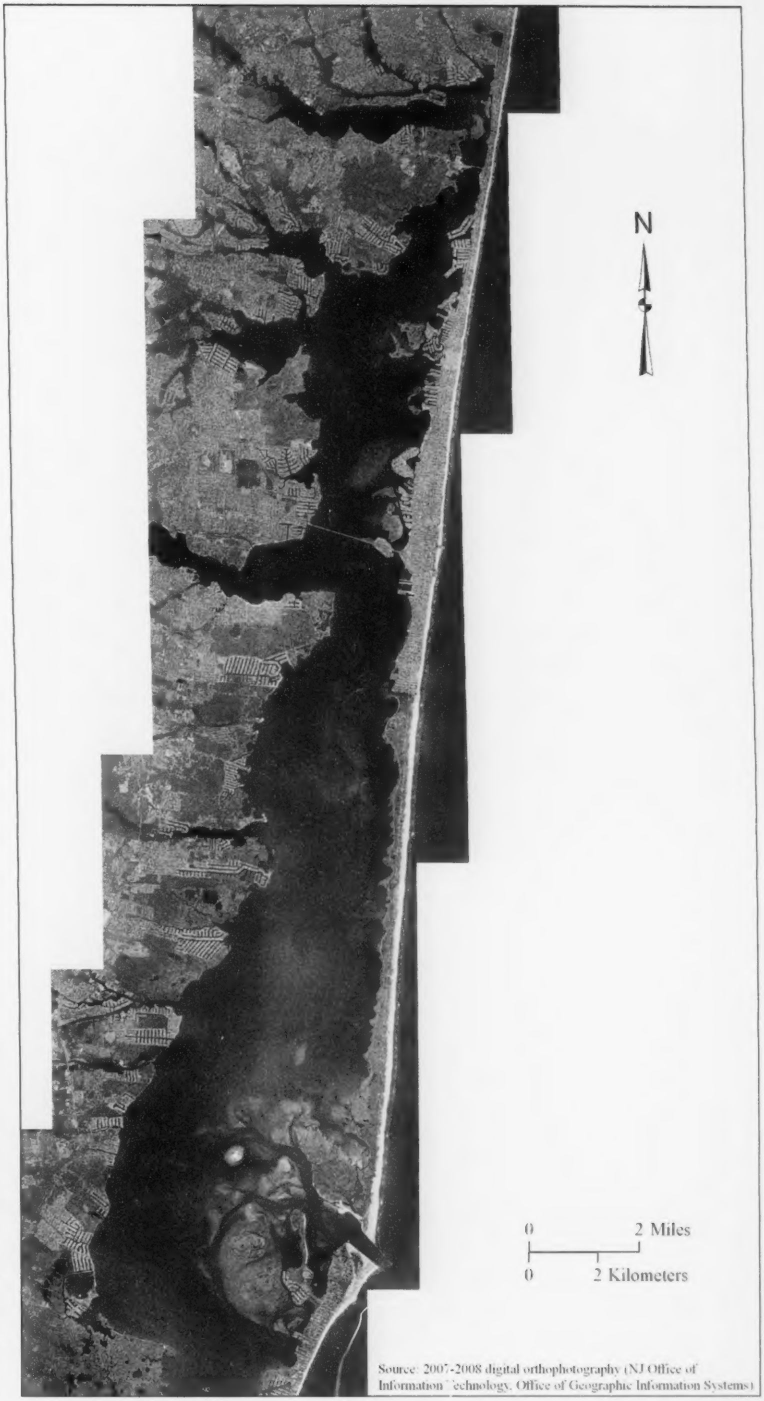


Figure 3.—Aerial view of Barnegat Bay, showing the extensive flood-tide delta at the Barnegat Inlet and the broad shelf along the estuarine margin of the barrier spit, formed by earlier flood-tide delta and overwash deposits.

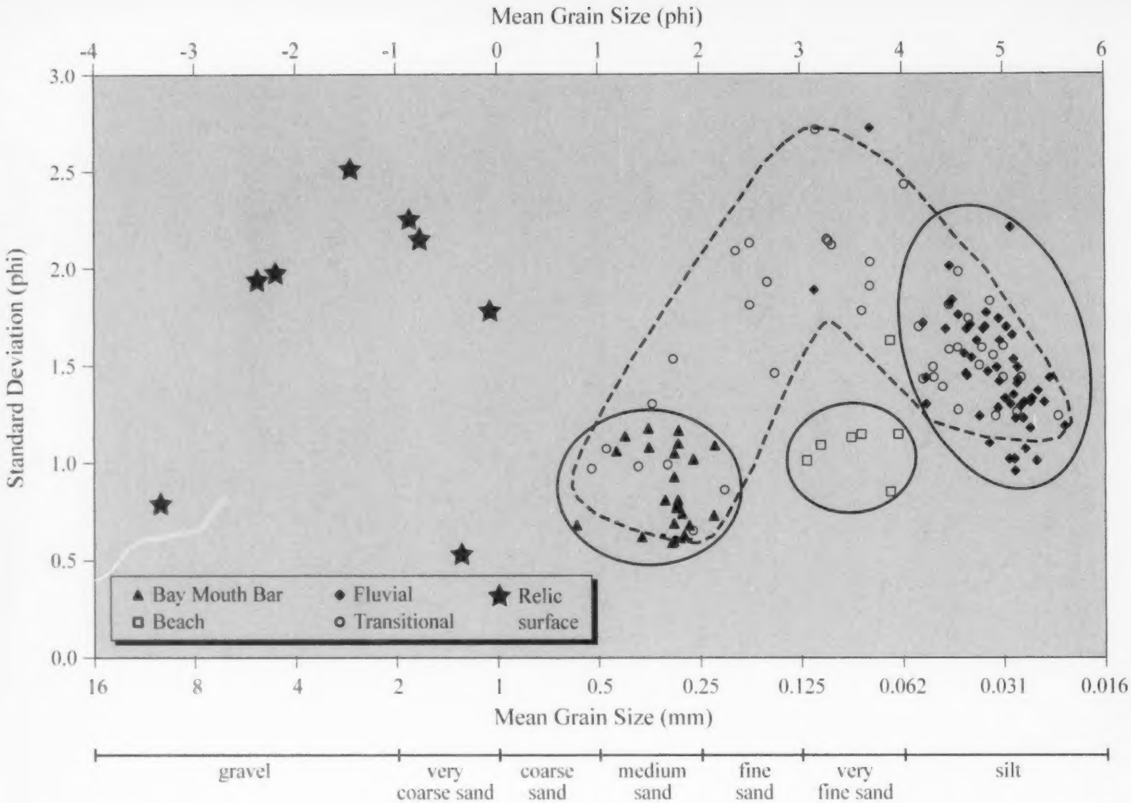


Figure 4.—Bivariate plot of sorting (standard deviation in phi units) and mean grain-size values of sediment samples from Kettle Creek–Silver Bay micro-estuaries, Barnegat Bay (after Psuty, 2004). Samples were collected from a variety of morphological features within and adjacent to the micro-estuaries. The relict surface has no recent sediment accumulation and thus has no relationship to the ambient processes.

peated in other estuarine situations that have similar current flow regimes and sediment availability.

### Great Egg Harbor Estuary

The Great Egg Harbor embayment is a complex estuary that incorporates a lagoon-type form along with a drowned river valley. It has one active inlet. At present, it encompasses an area of 22 km$^2$, has a coastal length of about 8 km, and a width that varies from about 1.0 km near its inlet to about 4.5 km inland from Ocean City, NJ (Fig. 5). The dominant tides are microtidal, with a range varying from about 1.52 m spring tide to 0.7 m neap tide at the inlet.[1]

There is an abundant coastal sediment supply being delivered from the erosion of a drowned delta to the north as well as sediment arriving from the south, transported from the Delaware River (McMaster, 1954; Dobday, 1981). The estuary has a large flood tide delta that occupies 3 km$^2$. There are deep channels along the margins of the tidal delta through which there is a counter-clockwise tidal current circulation (Psuty et al.[2]). The morpho-sedimentary units within the estuary are related to the geomorphological evolution of the barrier island and the flood tide delta building into Great Egg Harbor Inlet.

The present morpho-sedimentary pattern consists of a series of subaerial marsh islands atop a complex of very-fine sand shoals extending inland toward the drowned river channel (Fig. 5, 6). The major channels and their distributaries dissecting the flood-tide delta are sites of coarser sediments, usually with fine sand and shell lining the channel.

The channels near the inlet have high concentrations of shell debris covering the bottoms and coarser sediments. In places of very high tidal currents, the bottom sediments are composed of relic materials, the old Pleistocene surface which has no modern sediment accu-

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[1]Mean tide conditions are available for Great Egg Harbor on the NOAA Tides and Currents website located at: http://tidesandcurrents.noaa.gov/tides09/tab2ec2b.html#32

[2]Psuty, N. P., Q. Guo, and N. S. Suk, 1993. Sediments and sedimentation in the proposed ICWW Channels, Great Egg Harbor, NJ. Report submitted to O'Dea, Pavlo & Associates, 107 p.

mulation. These sites tend to be deeper and near the contact with the margin of the continent. All of the sand is derived from the marine side of the estuary and shallow cores demonstrate that the marine sand covers former bay habitats consisting of silty open-water deposits, and that habitats shifted from oyster beds at the base of the cores to hard clam environments at the core surface as sea level rose and salinity gradients changed (Psuty et al.[2]).

The Great Egg Harbor is a relatively small site, and it is dominated by the flood-tide delta composed of fine and very fine sand. There are deep channels that flank either side of the delta and one shallower channel that bisects the delta. The channels are the avenues of tidal flow and relatively coarser sediments in transport. The shoals extend through most of Great Egg Harbor and lie between the major channels. They form a shallow zone that connects with the mainland to the west of Great Egg Harbor. There is a grain-size gradient that has coarser material nearer the inlet and finer material inland. Sorting decreases inland as fluvial silts mix with the coastal sands, creating a softer bottom with modest changes in morphology, leading to good shellfish habitat. The deep channels at the margins of the flood tide delta tend to have a consistent depth and bottom type.

The quantity of sand entering the Great Egg Harbor estuary is apparently insufficient to maintain the complete flood-tide delta system. An analysis of the areal extent of the islands and the shoals from aerial photos covering the period of 1940 to 1991 (Guo and Psuty, 1997) reveals that the islands and shoals are diminishing in areal extent, a loss of 5% over this 51-year period, and shifting inland. Cores and grab samples also suggest that the islands and shoals are eroding on their inlet margin and extending inland. A few $C^{137}$ dates from the island indicate that the combined rate of sea-level rise and compaction in the very recent accumulations is on the order of 7 mm/yr (Psuty et al.[2]). That is a very large demand on the ambient sediment transport mechanisms to maintain the characteristics of the surface area of the

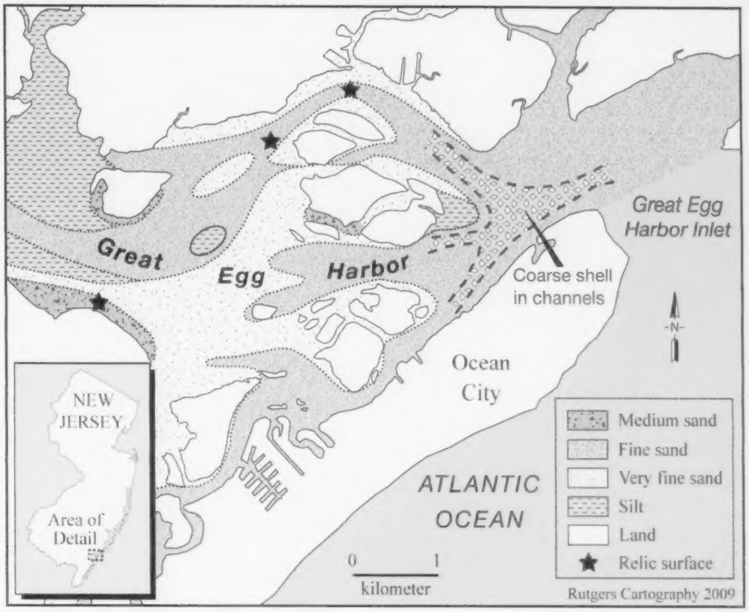


Figure 5.—Distribution of morpho-sedimentary units in Great Egg Harbor.

flood-tide delta, leading to a shift in the morpho-sedimentary units and a migration of the sites of shellfish abundance.

### Great South Bay

Great South Bay is a shore-parallel, lagoon-type estuary with one major inlet (Fire Island Inlet) and a secondary inlet (Moriches Inlet) that is connected to the ocean via the next embayment to the east (Moriches Bay). Great South Bay has an area of 217 km$^2$, a coastal length of about 37 km, and a width that varies from about 300 m at its eastern end to nearly 9 km at its western portion (Fig. 7). The dominant tides are microtidal, attaining a range of about 1.3 m at spring tide at the ocean side near the stabilized Fire Island Inlet.[3] Tidal range decreases greatly into the bay, with an average spring range from 0.21 to 0.62 m, lower ranges at greater distances from the inlet. Although there are some deep channels in portions of Fire Island Inlet, the estuary tends to have a broad gently-sloping shelf extending and deepening inland from the southern margin (ocean side). The deepest portion of the estuary is 3–4 m and it is nearer the inland margin of the bay. As with other lagoon-type estuaries, the distribution and makeup of the morpho-sedimentary units within the embayment are related to the geomorphological evolution of the ancestral barrier spit as it migrated inland and extended westerly (Bokuniewicz and Schubel, 1991).

In the past, there was a very abundant sediment supply available to construct the barrier island system along Long Island. Glacial outwash at and near the eastern end of Long Island provided great quantities of sand that was eroded and transported westerly (Taney, 1961; Williams, 1976; Rosati et al., 1999). The geomorphological features on Fire Island indicate that the island is composed of several smaller islands that have coalesced to form the present lengthy barrier (Psuty et al., 2005).

The presence of former inlets associated with the multi-island configuration of Fire Island is seen in the existence of broad flood-delta morpho-sedimen-

[3]Mean tide conditions are available for Great South Bay on the NOAA Tides and Currents website located at: http://tidesandcurrents.noaa.gov/tides09/tab2ec2a.html#20


Figure 6.—Aerial view of Great Egg Harbor, portraying the submarine and subaerial morphological features of the flood-tide delta and the shoals and channels associated with the riverine system.

tological units extending northerly into the bay that consist of medium sand near the barrier and grade to fine and very fine sand with silt toward the north (Bruderer, 1970; Rockwell, 1974; Jones and Schubel, 1980; Bokuniewicz and Schubel, 1991). The largest flood-delta deposit with a myriad of channels, shoals, and marsh islands extends inland from Fire Island Inlet (Fig. 7, 8). The sediments are well-sorted medium sands, coarsening with gravels and shell fragments lining the bottoms of the channels. Ali et al. (1976) distinguished components of the tidal deltas based on current flow regimes and noted that whereas the tidal channels had a distinctive high energy sediment-size distribution, the deeper embayment was often modified by the energy-absorbing eelgrass to create fine grain size accumulations. The very large flood-tide delta at Fire Island Inlet is probably related to the persistence of that inlet compared to other sites discharging into Great South Bay as well as the extensive migration of the inlet at the western margin of the barrier, more than 8 km from 1825 to 1941 (Smith et al., 1999; Allen et al., 2002).

A large flood-delta deposit is also found at the eastern end of Great South Bay, emanating from the aptly-named "Old Inlet" portion of Fire Island (Fig. 7, 8). Another major flood-delta extends from the Watch Hill region of the barrier island. The deepest areas near the mainland are sites of silt accumulations (Greene et al., 1978). They also tend to be associated with stream valleys cut into the mainland topography, and thus the morpho-sedimentary units at these sites are related to the pre-existing fluvial topography and to the fluvial sources of fine-grained sediments. In a few locations, beach deposits occur on the inland margin of the estuaries where exposure to waves and the presence of sand create the opportunity for sorting and transport of the sand at the water contact and for some distance offshore.

To the north of the barrier island and its flood delta extension, there is a considerable admixture of silt in the surface sands, increasing the silt content into deeper water. Vast seagrass beds occur in these portions of Great South Bay

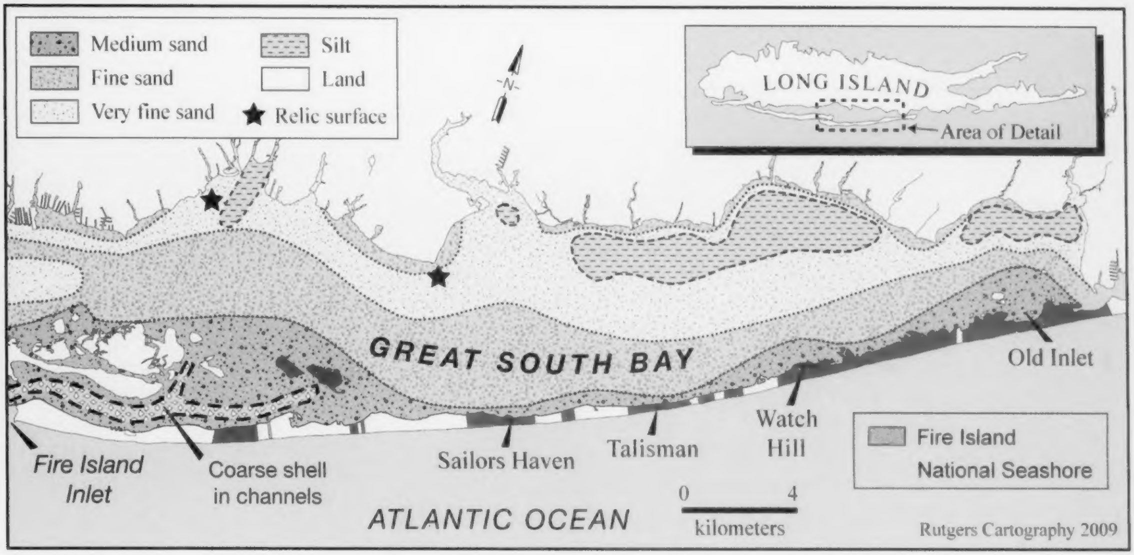


Figure 7.—Distribution of morpho-sedimentary units in Great South Bay.

(Greene et al., 1978). They modify the local tidal currents and ambient wave action and, together with the siltier sedimentary units, offer suitable habitat for shellfish.

### Shinnecock Bay

The Shinnecock Bay embayment incorporates an area of 33 km$^2$ and is a complex lagoon-type estuary with one active inlet. It has a coastal length of about 15 km and a width that varies from 0.6 km to about 4.5 km, with a general maximum depth of 3 m (Fig. 9). The semi-diurnal tides are microtidal, varying from about 1.01 m mean tide range at the inlet, to 0.86 at Ponquogue Point (2 km distance) and 0.74 m in the bay at a distance of about 4 km (Militello and Kraus, 2001). The estuary is shallowest at its southern margin, adjacent to the barrier, and has a general depth of about 3 m throughout much of the inner portion of the estuary. The morpho-sedimentary units within the estuary are related to the geomorphological evolution of the barrier spit as it migrated inland and extended westerly, and as it was breached by inlets at several locations, primarily in the eastern portion of the barrier (Morang, 1999).

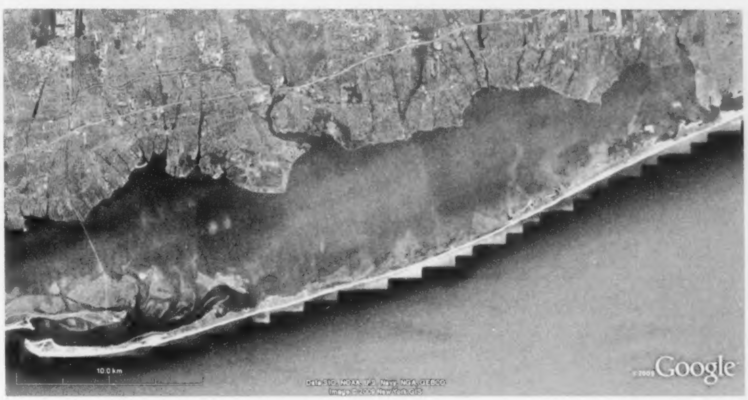


Figure 8.—Aerial view of Great South Bay, portraying the submarine and subaerial morphological features of the extensive flood-tide delta associated with the Fire Island Inlet and the flood-delta deposits from earlier inlets.

The Great Hurricane of September 1938 (Long Island Express) produced several sites of large washover across the barrier and into the estuary. This major storm also created the present Shinnecock Inlet, occupying a former inlet location, that migrated westerly until stabilized with jetties in 1952–55 (Rosati et al., 1999). The modern flood-tide delta is the most recent addition to the broad sandy shelf that is extending inland along the entire length of the barrier (Fig. 9, 10). The inlet margin of the delta is composed of the coarsest sediment (Pratt and Stauble, 2001); the dredged channels incorporate some gravel as well as shell debris and coarse sand that extend through and at the margins of the flood-tide delta (Dooley, 1974). Most of the shoal surface of the tidal delta as well as the shallow shelf along the inland margin of the barrier

is medium sand. Toward the inland margin of the shelf and shoal, and at greater depths, sediment is largely fine sand in and among seagrass beds.

The inland margin of the estuary is often the site of glacial-fluvial sediments that are worked by the ambient waves and currents to create narrow sandy beaches and sandy offshore zones. The variable glacial topography produces a patchwork of sediment types that continue into the estuary and contributes to a mix of morpho-sedimentary units at the inland portion of the estuary.

Shellfish habitat is limited near the barrier island because of planar morphology, shallow depths, and exposure to predators (MacKenzie et al., 2006). However, the deeper bay has greater morpho-sedimentological variety and a greater range of habitat characteristics.

## Pleasant Bay Estuary

The Pleasant Bay embayment is a complex estuary with an area of 29 $km^2$ and two active inlets toward its southern margin. The bay has a coastal length of about 11 km and a width that varies from less than 1 km at its northern portion to a maximum of about 5 km in the central portion (Fig. 11). The ocean tidal range is about 2 m at the inlet, at the limit of the microtidal classification. However, the tides decrease in range in the estuary, varying from about 1.58 m spring tide inside the inlet, to 1.13 m in Pleasant Bay, and to 0.4 m at the northern limits of the estuary.[4] The estuary is shallowest at its eastern margin, adjacent to the barrier, and deepest (maximum of 7 m) toward the northern contact with the continent. The morpho-sedimentary units within the estuary are related to the geomorphological evolution of the barrier spit as it migrated inland and extended southerly (Goldsmith, 1972).

Sediment supply consists largely of medium sand derived from erosion of the glacial deposits north of Chatham and the alongshore transport creating the Nauset Spit barrier. As the spit extended southward, considerable sand accumulated on the flood-tide-delta side of the barrier. Goldsmith (1972) suggested that the spit was periodically breached at an updrift location and a new inlet migrated southerly at some multi-decadal to centurial time scale. Recent inlet breaches, in 1958 (Hine, 1972), in 1987 (Borrelli, 2008), and 2007 have contributed to the morpho-sedimentological development. As a result, the flood-tide delta was rejuvenated at this temporal interval and repeatedly extended into the estuary.

The existing flood-tide delta is continuing to evolve and has a very complex pattern of channels (Fig. 11, 12). Some are inherited from the tidal flows associated with the 1987 inlet, and others are related to the 2007 inlet. Whereas most of the shoals in the flood-tide delta consist of medium sand, the channels are lined with coarse sand and shell debris. The estuary deepens quickly beyond the limits of the tidal delta and the sediments also grade quickly to fine and very fine sand. The central portion of Pleasant

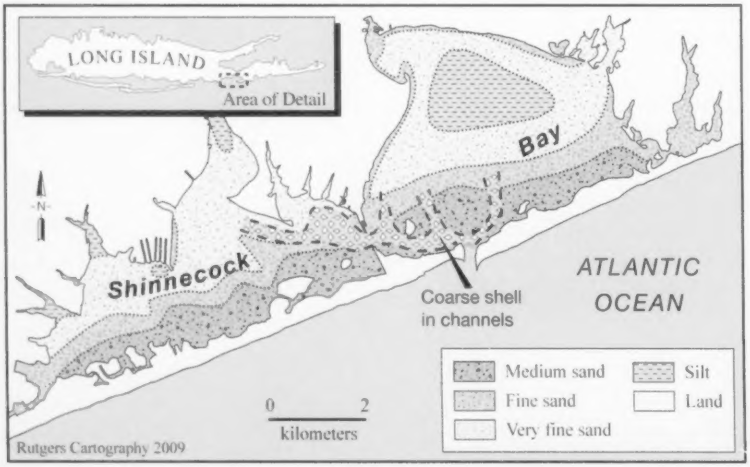


Figure 9.—Distribution of morpho-sedimentary units in Shinnecock Bay.

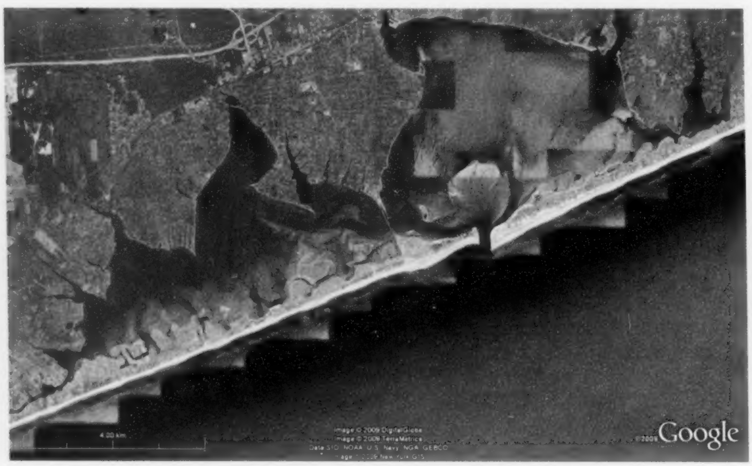


Figure 10.—Aerial view of Shinnecock Bay, portraying the submarine and subaerial morphological features of the flood-tide delta and the sandy shelf extending inland along the barrier.

[4]Mean tide conditions are available for Pleasant Bay on the NOAA Tides and Currents website located at: http://tidesandcurrents.noaa.gov/tides09/tab2ec1b.html#8

Bay has silt deposits. At a number of locations along the margin of the bay, erosion of the glacial deposits provides fine sand to accumulate as a localized beach feature and an associated sandy offshore slope.

The complex geomorphological history leads to a wide variety of shellfish habitats, ranging from deep abandoned channels lined with shell debris to moderately-deep silty pockets with seagrass beds. The 2007 inlet in Nauset Spit is causing a migration of shoals and channels and is redefining sites of shellfish abundance.

## Conclusions

The geomorphological characteristics of the selected microtidal estuaries in the northeastern U.S. are largely related to the dynamic evolution of the barrier island system over the past 3,000 years or so (young in a geological sense) and the concomitant transfers of sediment through inlets as well as overwash into the estuaries. The vectors of sediment transport in barrier island systems dictate that the greatest thickness of sediment and the coarsest sizes of sediment are at the seaward margin of the estuaries. Each of the estuaries is flood-tide dominant and, in general, each is shallowest at the seaward margin, except for the inlet channels, and deepens toward the mainland. The flood-tide deltas are the most dynamic component of the geomorphological system, accumulating great masses of sediment and extending into the estuaries.

In the natural progression of barrier island development and inlet migration, the flood-tide delta has shifted downdrift as the inlet migrated. The result was a continual expansion of the shallow shelf on the inland margin of the barrier island. As a consequence, the water depths tend to increase inland away from the barrier island and toward the mainland as a function of distance from the source of sediment input

Also, the deeper areas near the mainland are zones of accumulation of fine sediment, very-fine sand, and silts, derived from the fluvial sources draining the upland. Bottom types are therefore coarser toward the mouths of the estuaries and fine along an inland gradient. Sand is predominant in all of the estuaries. Silt is in isolated pockets near the mainland, often associated with

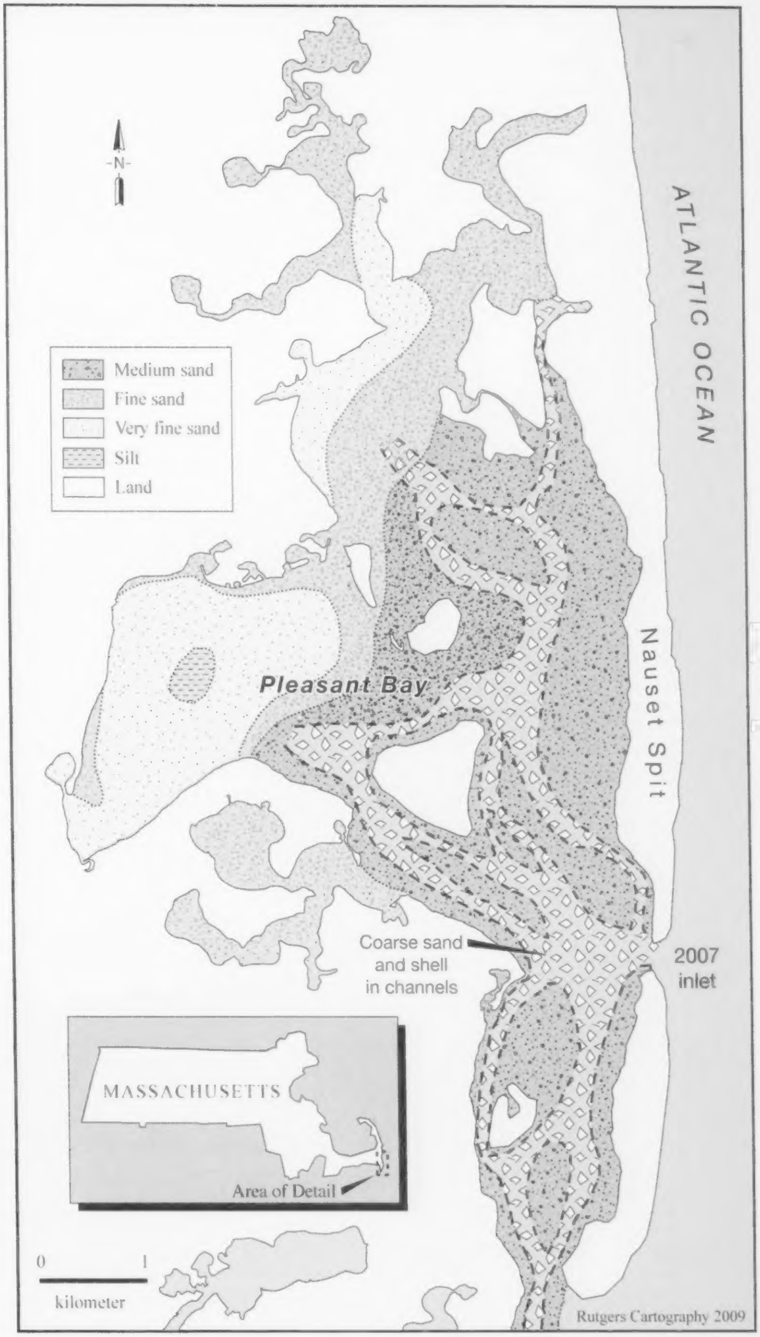


Figure 11.—Distribution of morpho-sedimentary units in Pleasant Bay.

some fluvial input. Shellfish habitat, therefore, improves away from the barrier islands as sediment types get finer, topographical variety ensues, and depths increase. Some of the estuaries, Shinnecock and Pleasant Bay, have a more dynamic morpho-sedimentary evolution because of the recent inlet development. The others are more stable and represent an end product of the evolutionary trend of microtidal barrier island estuarine environments. Overall, the pattern of bottom sediments is a product of a geomorphological process interacting with available sediment in a system of barrier island development under a sea-level rise scenario.


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Figure 12.—Aerial view of Pleasant Bay, portraying the submarine and subaerial morphological features of the flood-tide delta, the complex pattern of channels and shoals, and the recently-formed 2007 inlet.

## Literature Cited


Ali, S. A., R. H. Lindemann, and P. H. Feldhausen. 1976. Multivariate sedimentary environmental analysis of Great South Bay and South Oyster Bay, New York. Math. Geol. 8:283–304.

Allen, J. R., C. LaBash, P. August, and N. P. Psuty. 2002. Historical and recent shoreline changes, impacts of Moriches Inlet, and relevance to Long Island breaching at Fire Island National Seashore, N.Y. Dep. Inter., Natl. Park Serv. Tech. Rep. NPS/BSO-RNR/NRTR/2002-7, 76 p.

Bindoff, N. L., J. Willebrand, V. Artale, A. Cazenave, J. Gregory, S. Gulev, K. Hanawa, C. Le Quéré, S. Levitus, Y. Nojiri, C. K. Shum, L. D. Talley, and A. Unnikrishnan. 2007. Observations: oceanic climate change and sea level. *In* S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Avery, M. Tignor, and H. L. Miller (Editors), Climate change 2007: the physical science basis, p. 385–432. Contrib. Work. Group I Fourth Assess. Rep. Intergov. Panel Clim. Change, Camb. Univ. Press, Cambridge, UK.

Bokuniewicz, H. J., and J. R. Schubel. 1991. The origin and development of the Great South Bay: a geological perspective. *In* J. R. Schubel, T. M. Bell, and H. H. Carter (Editors), The Great South Bay, p. 7–10. State Univ. N.Y. Press, Stony Brook.

Borrelli, M. 2008. Sediment transport in a dynamic, tidally-influenced coastal embayment exemplified by Pleasant Bay and Cha-

tham Harbor, Cape Cod, Massachusetts. Ph.D. diss., Univ. R.I., Kingston, 154 p.
Bruderer, B. E. 1970. A preliminary investigation of the sediments of the Great South Bay, Long Island, New York. M.S. Thesis, Long Island Univ., Brookville, 86 p.
Cooper, J. A. G. 2001. Geomorphological variability among microtidal estuaries from the wave-dominated South African coast. Geomorphology 40:199–122.
Davies, J. L. 1964. A morphogenetic approach to world shorelines. Zeit. Geomorphol. 8:127–142.
Day, J. H. (Editor). 1981. Estuarine ecology: with particular reference to Southern Africa. A.A. Balkema, Rotterdam, 419 p.
Dobday, M. P. 1981. The Holocene geologic history of the Great Egg Harbor River estuary. M.A. Thesis, Temple Univ., Phila., 200 p.
Donnelly, J. P. 2006. A revised Late Holocene sea-level record for northern Massachusetts, USA. J. Coast. Res. 22 (5):1,051–1,061.
Dooley, D. W. 1974. A preliminary investigation of the sediments of Shinnecock Bay, Long Island, New York. M.S. Thesis, Long Island Univ., Brookville, 80 p.
FitzGerald, D. M., and J. Knight (Editors). 2005. High resolution morphodynamics and sedimentary evolution of estuaries. Coastal Systems and Continental Margins 8, Springer, N.Y., 364 p.
Goldsmith, V. 1972. Coastal processes of a barrier island complex and adjacent ocean floor: Monomoy Island-Nauset Spit, Cape Cod, Massachusetts. Ph.D. Diss., Univ. Mass., Amherst, 469 p.
Greene, G. T., A. C. F. Mirchel, W. J. Behrens, and D. S. Becker. 1978. Surficial sediment and seagrasses of eastern Great South Bay, N.Y. Mar. Sci. Res. Cent., Stony Brook, Spec. Rep. 12, 30 p.
Guo, Q., and N. P. Psuty. 1997. Flood-tide deltaic wetlands: detection of their sequential spatial evolution. Photogrammetric Eng. Remote Sensing 63:273–280.
Guo, Q., N. P. Psuty, G. Lordi, and C.-S. Tsai. 1997. Circulation studies in Barnegat Bay. *In* G. Flimlin and M. J. Kennish (Editors), Proceedings of the Barnegat Bay Workshop, p. 17–29. Coop. Ext. Ocean County, Toms River, N.J.
Hayes, M. O. 1975. Morphology of sand accumulation in estuaries: an introduction to the symposium. *In* L. E. Cronin (Editor), Estuarine Research, II, p. 3–22. Acad. Press, N.Y.
________ . 1980. General morphology and sediment patterns in tidal inlets. Sed. Geol. 26:135–156.
Hine, A. C. III. 1972. Sand deposition in the Chatham Harbor estuary and on the neighboring beaches. Master's Thesis, Univ. Mass., Amherst, 176 p.
Hunt, H. L. 2005. Effects of sediment source and flow regime on clam and sediment transport. Mar. Ecol. Prog. Ser. 296:143–153.
Isla, F. 1995. Coastal lagoons. *In* G. M. E. Perillo (Editor), Geomorphology and sedimentology of estuaries, p. 241–272. Dev. Sedimentol. 53, Elsevier, N.Y.
Jones, C. R., and J. R. Schubel. 1980. Distribution of surficial sediment and eelgrass in Great South Bay, New York (from Smith Point, west to Wantagh State Parkway). Mar. Sci. Res. Cent., Stony Brook, Spec. Rep. 19, 19 p.
Kennish, M. J. 1986. Ecology of estuaries I: physical and chemical aspects. CRC Press, Boca Raton, FL, 254 p.
________ . 2000. Barnegat Inlet, New Jersey: a case study of stabilization impacts. Bull. N.J. Acad. Sci. 45:13–18.
________ . 2001. Physical description of the Barnegat Bay–Little Egg Harbor estuarine system. *In* M. J. Kennish (Editor), Barnegat Bay—Little Egg Harbor, New Jersey: estuary and watershed assessment, p. 13–27. J. Coast. Res., Spec. Iss. 32.
Knight, J., and D. M. FitzGerald. 2005. Towards an understanding of the morphodynamics and sedimentary evolution of estuaries. *In* D. M. FitzGerald and J. Knight (Editors), High resolution morphodynamics and sedimentary evolution of estuaries, p. 1–10. Springer, N.Y.
MacKenzie, C. L., Jr., R. Pikanowski, and D. G. McMillan. 2006. Ampelisca amphipod tube mats may enhance abundance of northern quahogs *Mercenaria mercenaria* in muddy sediments. J. Shellfish Res. 25:841–847.
Mann, R., J. M. Harding, M. J. Southworth, and J. A. Wesson. 2005. Northern quahog (hard clam) *Mercenaria mercenaria* abundance and habitat use in Chesapeake Bay. J. Shellfish Res. 24:509–516.
McMaster, R. L. 1954. Petrography and genesis of the New Jersey beach sands. State N.J. Dep. Conserv. Econ. Develop., Trenton., Bull. 63, 259 p.
Militello, A., and N. C. Kraus. 2001. Shinnecock Inlet, New York, site investigation: Report 4, Evaluation of flood and ebb shoal sediment source alternatives for the west of Shinnecock interim project, New York. U.S. Army Eng. Waterway Exp. Stn., Vicksburg, MS. Tech. Rep. CHL-98-32, 212 p.
Morang, A. 1999. Shinnecock Inlet, New York, site investigation: Report 1, Morphology and historical behavior. U.S. Army Eng. Waterways Exp. Stn., Vicksburg, MS, Tech. Rep. CHL-98-32, 94 p.
Perillo, G. M. E. (Editor). 1995. Geomorphology and sedimentology of estuaries. Developments in Sedimentology 53, Elsevier, N.Y., 471 p.
Pratt, T. C., and D. K. Stauble. 2001. Shinnecock Inlet, New York, site investigation: Report 3, Selected field data report for 1997, 1998, 1999 velocity and sediment surveys., U.S. Army Eng. Waterway Exp. Stn., Vicksburg, MS, Tech. Rep. CHL-98-32, 19 p.
Psuty, N. P. 2004. Morpho-sedimentological characteristics of the Barnegat Bay–Little Egg Harbor estuary. *In* D. W. Davis and M. Richardson (Editors), The coastal zone: papers in honor of H. Jesse Walker, p. 81–92. Geosci. Man Ser. 38, La. State Univ., Baton Rouge.
________ , M. Grace, and J. P. Pace. 2005. The coastal geomorphology of Fire Island: a portrait of continuity and change (Fire Island National Seashore Science Synthesis Paper). U.S. Dep. Inter., Natl. Park Ser., Northeast Reg., Boston, Tech. Rep. NPS/NER/NRTR-2005/021, 70 p.
Rockwell, C. 1974. Recent sedimentation in the Great South Bay, Long Island, New York. Ph.D. Diss., Cornell University, Ithaca, N.Y., 147 p.
Roman, C. T., N. Jaworski, and F. T. Short. 2000. Estuaries of the northeastern United States: habitat and land use signatures. Estuaries 23:743–784.
Rosati, J. D., M. B. Gravens, and W. G. Smith. 1999. Regional sediment budget for Fire Island to Montauk Point, New York, USA. *In* N. C. Kraus and W. G. McDougal (Editors), Coastal Sediments '99, p. 802–881. Am. Soc. Civil Eng., Reston, VA.
Smith, W. G., K. Watson, D. Rahoy, C. Rasmussen, and J. R. Headland. 1999. Historic geomorphology and dynamics of Fire Island, Moriches and Shinnecock Inlets, New York. *In* N. C. Kraus and W. G. McDougal (Editors), Coastal Sediments '99, p. 1,597–1,612. Am. Soc. Civil Eng., Reston, VA
Taney, N. E. 1961. Geomorphology of the south shore of Long Island, New York. Beach Erosion Board, U.S. Army Corps Eng., Fort Belvoir, VA, Tech. Memo. 128.
Walker, H. J., and J. M. Coleman. 1987. Atlantic and Gulf Coastal Province. *In* W. L. Graf (Editor), Geomorphic systems of North America, p. 51–110. Geol. Soc. Am., Boulder, CO.
Williams, S. J. 1976. Geomorphology, shallow sub-bottom structure, and sediments of the Atlantic inner continental shelf off the Long Island, New York. U.S. Army Corps Eng., Coast. Eng. Res. Cent., Fort Belvoir, VA, Tech. Pap. 76-2, 123 p.

# Small-scale Commercial Culturing of Northern Bay Scallops, *Argopecten irradians irradians*, in Atlantic United States and Canada

CLYDE L. MACKENZIE, JR.

## Introduction

This paper describes the development of a new edible northern bay scallop, *Argopecten irradians irradians*, product. The concept of culturing northern bay scallops was considered in the early 1900's by Belding (1910), but he could not raise the larvae and stated that hatchery production could not be put on a practical basis.

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ABSTRACT—*In recent decades, hatchery-growout culture of oysters,* Crassostrea virginica, *and northern quahogs,* Mercenaria mercenaria, *has been commercially successful in Atlantic United States and oysters in Atlantic Canada. Culturists have not had success, as yet, with northern bay scallops,* Argopecten irradians irradians. *Large mortalities occur during the culture process, mainly because the scallops are relatively delicate and some die when handled. In addition, too little edible meat, i.e. the adductor muscle, is produced for the culture operation to be profitable. However, three companies, one in Massachusetts, one in New Brunswick, and one on Prince Edward Island, Canada, have discovered that they can produce bay scallops successfully by harvesting them when partially- to fully-grown and selling them whole. In restaurants, the scallops are cooked and served with all their meats (adductor muscles and rims) and also with the shells, which have been genetically-bred for bright colors. The scallop seed are produced in hatcheries and then grown in lantern or pearl nets and cages to market size. Thus far, production has been relatively small, just beyond the pilot-scale, until a larger demand develops for this product.*

By using better equipment and adequate foods for feeding larvae, Loosanoff and Davis (1963) were able to bring the bay scallop and many other bivalve mollusks through their larval stages to set consistently. Their paper and another by Walne (1974) stimulated much further work to develop techniques and find the best larval foods to advance production of commercial quantities of the mollusks (Castagna and Duggan, 1971; Castagna, 1975; Rhodes and Widman, 1980).

Hatchery-growout production of bivalve mollusks now is common in numerous locations in the world. Juvenile scallops are also collected from the wild for further growth to market sizes in controlled environments, such as lantern nets, pearl nets, and trays. On a large scale, various species of scallops are cultured in China (Gou et al., 1999; Guo and Luo, 2006), Chile (von Brand et al., 2006), Mexico (Mazon-Suastegui et al., 2003), Scotland (Edwards, 1997), and in Atlantic Canada (Quebec, Newfoundland, Nova Scotia), and also St. Pierre and Miquelon, France (where North Atlantic sea scallops, *Placopecten magellanicus*, are grown) (Davidson and Mullen, 2005).

In New York and Massachusetts in the United States and in Atlantic Canada, development groups have attempted to produce the northern bay scallop commercially by growing their larvae in hatcheries and then rearing the juveniles to full market size in suspended nets and cages; only the adductor muscle of the scallop would be sold.

This species will not grow to full size during one growing season, spring through fall, and the scallops must be held over winter and grown further during the following warmer months. When held that long, most scallops do not survive, though, and since only the scallops' adductor muscle was to be sold, this type of culture has not as yet been profitable (Castagna[1], Gaines[2], Rivara[3], Zatila[4]).

## Successful Commercial Bay Scallop Culturing

In recent years, a few small companies in Massachusetts and two–three others in New Brunswick and Prince Edward Island, Canada[5] have tried growing bay scallop seed and then harvesting the scallops, some at smaller than usual sizes, for sale (Fig. 1). All the scallops have been bred to grow bright orange, yellow, purple, or white shells (Fig. 2), rather than the brownish and grayish shells typical of wild scallops. The beautiful design of the bay scallop shell has been used as a decoration for centuries (Cox, 1957; MacKenzie, 2008a), and these shells, especially being brightly-colored, have enhanced the appearance of food presentations on restaurant serving plates (Fig. 3a, b).

Adamkewicz and Castagna (1988) found that a single gene controls the presence or absence of color in the scallop's shell. One or more additional

[1]Castagna, M. Biologist, Virginia Institute of Marine Science, Wachapreague, VA, Personal commun., 1985.

[2]Gaines, W. Shellfish constable, Edgartown, Mass., Personal commun., 2008.

[3]Rivara, G. Biologist, Cornell University Extension, Southold, N.Y. Personal commun., 2004.

[4]Zatila, J. Official, F. M. Flower Company, Bayville, N.Y. Personal commun., 2006.

[5]Morrison, A. Biologist, Prince Edward Island Department of Fisheries, Agriculture, and Rural Development, Charlottetown, Canada. Personal commun., 2009.

Figure 1.—Crewman of private culturist harvesting 10-tier lantern nets that hold bay scallops. The lantern nets are suspended from long-lines in Nasketucket Bay, Mass., May, 2009. Note: All photographs by C. L. MacKenzie, Jr.

Figure 2.—Brightly-colored bay scallops after being taken from lantern nets and before being cleaned of fouling organisms for marketing, Nasketucket Bay, Mass.

Figure 3a.—A restaurant's evening serving of 5 bay scallops, 5 blue mussels, *Mytilus edulis*, 5 shrimp, lobster, and greens with sauces. The brightly-colored bay scallop shells enhance the presentations of the restaurant servings.

Figure 3b.—A restaurant's luncheon serving of 3 bay scallops, 3 blue mussels, and 3 shrimp with sauces.

genes determine the distribution of overlying pigments and the background color of the shell that may be orange, yellow, or white with orange; yellow is dominant over white.

Thus far, one company in Massachusetts, one in New Brunswick, and another on Prince Edward Island have cultured the scallops with economic success. The others abandoned it because profits were too small (The gear used is expensive and too few scallops were produced), or else they have continued on a pilot scale. Restaurants have cooked and served the entire meats (adductor muscles and rims) of the scallops rather than only the muscles. The meats have been sautéed, grilled, or steamed and served in their shells.

## United States Production

The Massachusetts company, Taylor Cultured Seafood[6] in the town of Fairhaven, raises bay scallops and oysters in Nasketucket Bay, an arm of Buzzards Bay on its north side. Chew (1993) briefly described its bay scallop culture operations. Currently each June, the company obtains about 6 million 1–3 mm seed bay scallops from a hatchery located in Maine. The seed are grown to a height of 5 mm (0.2 in) in flupsies (upwellers) and are then transferred to fine-meshed nets. As growth progresses, the seed are transferred to lantern nets that have coarser netting that allows for more water circulation. Water depth at the lease site where the scallops are grown is as much as 9 m (30 ft). Scallop mortality is at least 50% during their first 3 months; some mortality continues during all months, but is least in the fall.

From several to 12 months later, the survivors are harvested at a shell height of 60–70 mm (2.5–2.75 in), or about full size (Fig. 4, 5, 6). The company harvests both the scallops and the oysters on market demand every few days year-round. As many as 2 million scallops (4,000–5,000 bushels) are marketed each year. Production has been limited by market demand.

The scallops are sold to a wholesaler who distributes them for about $0.40 each to restaurants. Properly chilled, the scallops have a shelf life of about one week. Restaurants serve from 3 to 6 scallops with the shells on a plate, some-

[6]Mention of the names of commercial firms does not imply endorsement by the National Marine Fisheries Service, NOAA.

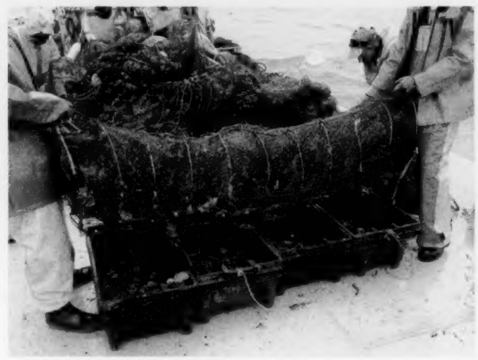

Figure 4.—(above) Bay scallops receive good water circulation inside the tiers of large-mesh lantern nets, Nasketucket Bay, Massachusetts.

Figure 5.—(above right) Live bay scallops and the shells of dead scallops in the bottom tier of a lantern net, Nasketucket Bay, Mass.

Figure 6.—(right) A crew emptying bay scallops, destined for market, from a lantern net into tubs. The lantern net holds about a bushel of market-sized scallops, Nasketucket Bay, Mass.

times by themselves with sauces such as liquid corn, but commonly with blue mussels, *Mytilus edulis*, and shrimp and also some lobster, with tomato sauces in Italian restaurants and with various types of sauces and also greens in others. The scallops acquire the flavor of the sauces, and if a diner wants to savor the flavor of the scallop meats it is best to consume them steamed. So prepared, the flavor is similar to that of steamed softshell clams, *Mya arenaria*. Restaurants in southeastern Massachusetts that serve the scallops have been selling about 100 dishes/week but, when busiest, some have been selling as many as 25/day.

## Canadian Production

The New Brunswick company, Etang Ruisseau Bar Ltd.[6] in Shippegan, operates in much the same manner as Taylor Cultured Seafood, but few bay scallops survive the Canadian winters. The company produces seed oysters and bay scallops in its own hatchery. The seed are grown in lantern nets in Baie St. Simon in northeastern New Brunswick. The scallops are harvested when their heights are 55–65 mm (2.2–2.6 in), beginning on 1 Nov. (4.5 months after the larvae have settled and begin to grow) and ending by mid January. In Canada, the peak demand for them is for meals at home on Christmas Eve and New Year's Eve. They are prepared by steaming them whole in their shells. After mid January, about 10% of the scallops die from the cold each week. Few remain alive by the following spring. The annual quantity of bay scallops the company produces is unknown, but it is smaller than Taylor's in Massachusetts.

A company selling shellfish under the names, Atlantic Mussel Products[6], and Prince Edward Island Mussel King[6], in Morell, P.E.I., has produced bay scallops in similar quantities to Etang Ruisseau Bar Ltd. in the years of its highest production. The seed are obtained from Etang Ruisseau Bar Ltd. at a size of 2–3 mm in mid June. The company has had problems producing the scallops every year because large numbers of tunicates (3 species) may settle and grow on its plastic holding cages and aluminum racks and form a cover over the nettings. The cover can reduce water flows to such an extent that the scallops cannot grow large enough for commercial sales. In successful years, the company has harvested about 10,000 lbs: 130,000 scallops (13 scallops/lb), equal to 200 bushels. It sells the scallops for $4.00/lb ($0.31/scallop). Shipments are made in waterproof boxes that each hold four 10-lb bags of live scallops and 10 lbs of ice; they go to Toronto, Boston, New York, and other markets. The Canadian bay scallops shipped to the United States eventually are received by restaurants and prepared similarly to the Massachusetts scallops.

Some cultured bay scallops have spawned and produced natural (wild) populations in Nova Scotia and Prince Edward Island. Their survival has been extremely low in the coldest winters, and thus their quantities are small. The natural scallops apparently were eliminated by a recent cold winter on Prince Edward Island. The scallops have

survived in Merigomish Harbor, Nova Scotia, and in years of good setting enough have survived in subsequent warm winters to provide a commercial crop on a 5-acre lease. During September and November, the lease-holder has gathered at least 300–400 scallops/day by hand as he waded in waters at low tide. The scallops have been shipped live in chilled coolers to the Halifax Farmers' Market. Its retailers sell them to restaurants and home-makers by the pound: 12 to 20 whole scallops/pound. The scallops are steamed similarly to blue mussels and their entire meats are consumed (Bagnall[7], Docker[8]).

## Overview

In Massachusetts, a positive marketing feature of this bay scallop product is its availability to restaurants year-round, including during July–August, this being the time of peak numbers of tourists desiring meals of seafoods. The sales of the Canadian bay scallops in November–December miss this summer period of high consumer demand. The marketing months of the Canadian bay scallops are about the same as those when most northern bay scallops are harvested from beds of naturally-occurring bay scallops from New York–Massachusetts. The scallops, harvested for only their adductor muscles, are sold mostly in fish and supermarkets, usually for home meals rather than for restaurant meals.

[7]Bagnall, A. G. Supervisor of Extension Service, Nova Scotia Fisheries and Aquaculture, Halifax, Canada. Personal commun., 2009.

[8]Docker, P. Shellfish Leaseholder, Merigomish, Nova Scotia, Canada. Personal commun., 2009.

Dishes of cooked whole meats and attractive shells of bay scallops are a new food product that has not been mentioned in recent articles about the scallop fishery (MacKenzie, 2008b). If more people go to restaurants seeking the dish, this type of hatchery-growout culture of northern bay scallops undoubtedly will expand.

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## Literature Cited

Adamkewicz, L., and M. Castagna. 1988. Genetics of shell color and pattern in the bay scallop, *Argopecten irradians*. J. Heredity 79(1):14–17.

Belding, D. L. 1910. A report upon the scallop fishery of Massachusetts, including the habits, life history of *Pecten irradians*, its rate of growth, and other facts of economic value. Wright and Potter Printing Co., State Printers, Boston, 150 p.

Castagna, M. 1975. Culture of the bay scallop, *Argopecten irradians*, in Virginia. Mar. Fish. Rev. 37(1):19–24.

________ and W. P. Duggan. 1971. Rearing of the bay scallop, *Aequipecten irradians*. Proc. Natl. Shellfish Assoc. 61:80–85.

Chew, K. K. 1993. Bay scallop culture: a reality in Massachusetts. Aquaculture Mag. 19(6):84.

Cox, I. (Editor). 1957. The scallop, studies of a shell and its influences on mankind. The 'Shell' Transport and Trading Co., Limited, Lond., 135 p.

Davidson, L.-A., and J. Mullen. 2005. Proceedings of the scallop aquaculture workshop: Halifax, Nova Scotia. 24 Jan. 2004. Can. Tech. Rep. Fish. Aquat. Sci. 2610, 37 p.

Edwards, E. 1997. Molluscan fisheries in Britain. *In* C. L. MacKenzie, Jr., V. G. Burrell, Jr., A. Rosenfield, and W. L. Hobart (Editors), The history, present condition, and future of the molluscan fisheries of North and Central America and Europe, vol. 3, Europe, p. 85–99. U.S. Dep. Commer., NOAA Tech. Rep. 129.

Gou, X., S. E. Ford, and F. Zhang. 1999. Molluscan aquaculture in China. J. Shellfish Res. 18:19–31

________ and Y. Luo. 2006. Scallop culture in China. *In* S. E. Shumway and G. J. Parsons (Editors), Scallops: biology, ecology and aquaculture, p. 1,143–1,161. Elsevier Develop. Aquacult. Fish. Sci. 35, N.Y.

Loosanoff, V. L., and H. C. Davis. 1963. Rearing of bivalve mollusks. 1963. Adv. Mar. Biol., Acad. Press. 1:1–136.

Mackenzie, C. L., Jr. 2008a. History of the bay scallop, *Argopecten irradians*, fisheries and habitats in Eastern North America, Massachusetts through northeastern Mexico (Preface). Mar. Fish. Rev. 70(3–4):1–5.

________. 2008b. The bay scallop, *Argopecten irradians*, Massachusetts through North Carolina: its biology and the history of its habitats and fisheries. Mar. Fish Rev. 70(3–4):6–79.

Mazon-Suastegui, J. M., M. Robles-Mungaray, and M. Osuna-Garcia. 2003. Bases tecnológicas para el cultivo de la conchuela *Argopecten ventricosus* en la Republica de Panamá. Una publicación de la Dirección de Divulgación del Ministerio de Desarrollo Agropecuario de Panamá, en el marco del Convenio de Cooperación Cientifica-Técnica México-Panamá, S.R.E.-IMEXCL 302NP13 Y 302PN037-FASE II, 54 p.

Rhodes, E. W., and J. C. Widman. 1980. Some aspects of the controlled production of the bay scallop (*Argopecten irradians*). Proc. World Maricult. Soc. 11:235–246.

von Brand, E., G. E. Merino, A. Abarca, and W. Stotz. 2006. Scallop fishery and aquaculture in Chile. *In* S. E. Shumway and G. J. Parsons (Editors), Scallops: biology ecology and aquaculture, p. 1,293–1,314. Elsevier Develop. Aquacult. Fish. Sci. 35, N.Y.

Walne, P. R. 1974. Culture of bivalve mollusks. 50 years' experience at Conwy. Fish. News (Books) Ltd., Lond., 173 p.

# History of Molluscan Fishery Regulations and the Shellfish Officer Service in Massachusetts

HENRY LIND

## Introduction

The beds of oysters, *Crassostrea virginica*, and softshell clams, *Mya arenaria*, on the south coasts of Cape Cod Bay, Mass., must have staggered the minds of the settlers of the Plymouth Colony in the 1620's because they were extensive and well populated. The outer section of the Cape Cod peninsula was named Eastham, with reference to a section of London known as East Ham, and it included what is now known as Wellfleet, Eastham, and Orleans (Fig. 1). This area so reminded the settlers of the bountiful Billingsgate ward of London that they gave that part of the land the same name. The town of Eastham was incorporated in 1651. From 1641 to 1647, every family was permitted unlimited harvest of the oysters and softshell clams for home consumption and use as bait for catching finfish (Pratt, 1844).

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*ABSTRACT—Oysters,* Crassostrea virginica, *and softshell clams,* Mya arenaria, *along the Massachusetts coast were harvested by European colonists beginning in the 1600's. By the 1700's, official Commonwealth rules were established to regulate their harvests. In the final quarter of the 1800's, commercial fishermen began harvesting northern quahogs,* Mercenaria mercenaria, *and northern bay scallops,* Argopecten irradians irradians, *and regulations established by the Massachusetts Legislature were applied to their harvests also. Constables (also termed wardens), whose salaries were paid by the local towns, enforced the regulations, which centered on restricting harvests to certain seasons, preventing seed from being taken, and personal daily limits on harvests. In 1933, the Massachusetts Legislature turned over shellfisheries management to individual towns. Local constables (wardens) enforced the rules. In the 1970's, the Massachusetts Shellfish Officers Association was formed, and was officially incorporated in 2000, to help the constables deal with increasing environmental problems in estuaries where fishermen harvest mollusks. The constables' stewardship of the molluscan resources and the estuarine environments and promotion of the fisheries has become increasingly complex.*

This paper describes the regulations enacted to conserve the molluscan stocks because they were being harvested in increasingly larger quantities as time passed, and the development of the Massachusetts shellfish officer service (Table 1) (Fig. 2). Some of the information was obtained from town records in Eastham and a book authored by R. A. Rider (1989).

## First Regulations

Massachusetts coastal communities have had "wardens" for many years who were responsible for the management and oversight of the towns' fisheries (Fig. 3). In the first half of the 1700's, the unregulated taking of game, fish, and shellfish drove many species to the brink of extinction. In 1739, Massachusetts enacted game laws and employed "State Game Wardens" to enforce environmental laws. Many towns appointed their own, mostly volunteer "Game Protectors" (Malone[1]). By 1769, harvesting had diminished the molluscan stocks substantially. A description of the oyster fishery in the northern part of the town now named Wellfleet stated "... Oysters were found in great abundance on the flats, at the first settlement but at this time the number of people had so increased and such quantities were taken for local consumption and for Boston market, that it became necessary to prevent their entire destruction for the district to take measures to preserve and propagate them" (Pratt, 1844). In 1772, an Act of the General Court of Massachusetts was passed regulating the taking of oysters in Billingsgate Bay (near Wellfleet). The residents disagreed and, "Now voted by the district to ask the court to repeal the act so that in the three summer months they should not be taken for Boston market, nor in July and August for the use of the inhabitants" (Pratt, 1844).

In 1773, the inhabitants of the town voted to the effect that "whereas the oyster fishery in this district was the principal support of many of the inhabitants and of great advantage to the province in general and whereas it had been greatly hurt and damaged by persons taking the young oysters and would be ruined if not timely prevented, it was agreed to make and adopt bylaws to preserve them. A committee was chosen to enforce the penalty against all persons who should violate the regulations" (Pratt, 1844). Thus perhaps the first enforcement there was accomplished by committee. After 1773, shellfish became a town responsibility for the first time (Rider, 1989). There is some evidence that the colonial subjects were frustrated with the British rule and perhaps this factored into the general sentiment

[1]Malone, Brian G., Director of Natural Resources, Town of Dennis, Mass., Personal commun., 2009.

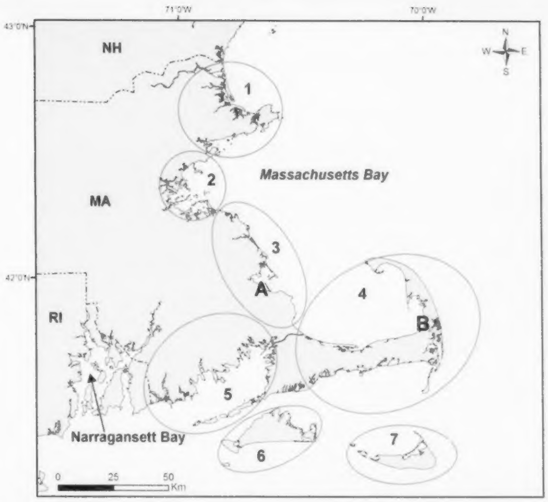



Figure 1.—Location A was the site of the Plymouth Colony, and Location B was the site of Eastham. The coastline of Massachusetts has been grouped into 7 areas that contain towns or cities producing commercial mollusks. Area 1 has 12 towns: Salisbury, Newburyport, Newbury, Rowley, Ipswich, Essex, Gloucester, Rockport, Manchester, Beverly, Marblehead, and Salem—principal species: softshell clams; Area 2 has 10 towns: Swampscot, Lynn, Nahant, Revere, Winthrop, Boston, Quincy, Weymouth, Hingham, and Hull—principal species: softshell clams; Area 13 has 6 towns: Cohasset, Scituate, Marshfield, Duxbury, Kingston, and Plymouth—principal species: softshell clams and oysters; Area 4 has 13 towns: Sandwich (no fishery but shares one with Bourne), Barnstable, Dennis, Brewster, Eastham, Wellfleet, Truro, Provincetown (shares a fishery with Truro), Orleans, Chatham, Harwich, Yarmouth, and Mashpee—principal species: quahogs, softshell clams, oysters, and bay scallops; Area 5 has 8 towns: Bourne, Falmouth, Wareham, Mattapoisett, Fairhaven, New Bedford, Dartmouth, and Westport—principal species: bay scallops, quahogs, and oysters; Area 6 has 6 towns: Oak Bluffs, Edgartown, West Tisbury, Tisbury (Vineyard Haven), Chilmark, and Aquinnah—principal species: bay scallops and quahogs; and Area 7 has 1 town: Nantucket—principal species: bay scallops.

Figure 2.—A shellfish constable is discussing matters with a softshell clam harvester in Orleans. The photographers of this and all other images were various shellfish constables.

**Table 1.—History of actions to protect natural resources in town of Dennis, Mass. (Malone[1]).**

| Year | Actions |
|---|---|
| 1869 | Fish Committee formed. |
| 1903 | Town appoints first volunteer "Fish Wardens." |
| 1935 | Town appoints volunteer "Fish and Game Wardens." |
| 1936 | Town appoints volunteer "Shellfish and Clam Wardens." |
| 1939 | Town appoints volunteer "Shellfish Constables." |
| 1941 | Town appoints first full-time salaried "Shellfish Constable." |
| 1963 | Town appoints a person to position of "Conservation Officer." |
| 1969 | Town adds two assistant positions to town roster: 1) assistant "Shellfish Constable" and assistant "Conservation Officer." |
| 1975 | Title of "Conservation Officer" is changed to "Natural Resource Officer." The title "Shellfish Constable remained. |

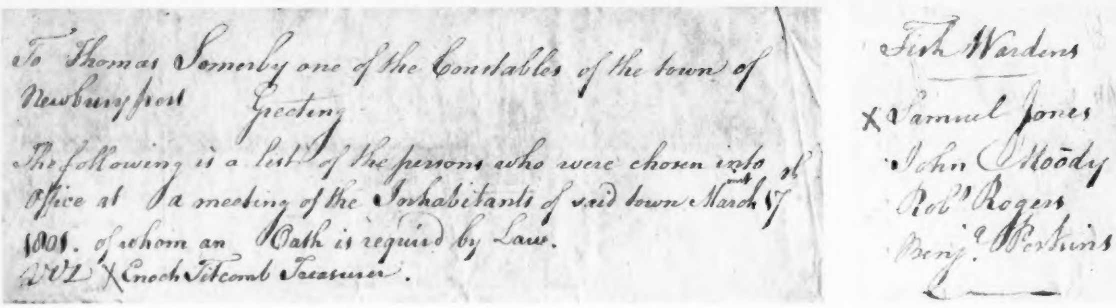
[1] Malone, Brian G., Director of Natural Resources, Town of Dennis, Mass., Personal commun., 2009.

regarding the revolutionary tone of the times. In 1781, a town meeting in Wareham voted to join with the town of Sandwich to ask the Massachusetts General Court to pass an act to preserve the shellfish (Rider, 1989).

In 1763, what is now Wellfleet, which had large oyster populations, became a separate entity, and soon after the American Revolution, 1775–83, the large land area of Eastham began to be further divided. In 1797, the southerly portion known as Orleans became an independent town. Included in the articles of separation were the rights to the shellfishery of either Eastham or Orleans to be retained by the inhabitants of the other as if they were residents of that town. A resident of one town could purchase a commercial permit in the other town as if they were a resident of that town. This remains one of the few instances of towns in the commonwealth where the shellfishery was shared on a commercial level between neighboring towns. In addition, the towns recognized the need for regulations and their enforcement to protect the molluscan resources due to their high value. The threat of overfishing oysters was so great that the town selectmen voted to choose a committee to "prosecute the inhabitants of other towns if they took oysters in the town of Orleans" (Pratt, 1844).

At the time, the total harvest of softshell clams was listed as 100 barrels with a value of $5.00 per barrel. Later estimates of the quantity of the clams in the Pleasant Bay section of Orleans was 500 barrels in 1800 and 1,000 barrels in 1802; from 12 to 18 bushels were required to fill a barrel which was then worth $6.00 when full. From 100 to 200 persons were employed at least part-time in the fishery. The economic value of a bushel of clams was equal to that of 6–8 bushels of corn.

The first committee on shellfish in Wareham was appointed at the annual town meeting on 6 March 1819. The subsequent committees were chosen at each annual town meeting up to 1902.


To Thomas Somerby one of the Constables of the town of
Newburyport Greeting
The following is a list of the persons who were chosen into
Office at a meeting of the Inhabitants of said town March 17
1801. of whom an Oath is required by Law.
X Enoch Titcomb Treasurer.

Fish Wardens
X Samuel Jones
John C Moody
Robt Rogers
Benjn Perkins

Figure 3.— Fish Wardens of Newburyport chosen along with other town officers in 1801.

A single person later was chosen by ballot to be the shellfish warden, overseeing the shellfish and the river herring, *Alosa pseudoharengus* (alewife) and *Alosa aestivalis* (blueback). In the mid 1800's, the position was absorbed into the harbormaster's duties (Rider, 1989). The concept of shellfishery management grew slowly in the 1800's, perhaps beginning with a reference in 1829 to a town meeting in Eastham which in awarding a petition to raise oysters advised, "That no person shall steal the same." Still, different species were often viewed and treated differently (Pratt, 1844).

The term "inexhaustible supply" was used by Pratt (1844) to describe the clam populations because their supply on the flats would recover completely in 2 years after having been mostly "fished out," due to regular sets of seed. The concept of protection appears to have been aligned more with economic stability than ecological well-being.

During the 1800's, the overall control of the laws pertaining to shellfisheries was in the hands of the Commonwealth of Massachusetts. They were overseen by the Commonwealth Fish and Game Commission, at least in the early 1900's. However, various efforts were under way to allow local towns or groups of towns to have some control of their own shellfisheries. Ingersoll (1887), in his descriptions of the shellfisheries of Massachusetts in the 1870's, stated that town laws placed regulations of the local beds into the hands of the town selectmen who then issued annual licenses to local citizens to harvest the mollusks. The town clerks in each town physically issued the shellfish licenses (*Fairhaven Star*, 9 Oct. 1897).

Enforcers of laws were local officers under the employment of the towns. Eastham established positions with the titles, "Fish Warden" and "Fish Constable" to enforce the rules. In some towns, the officers were referred to as wardens or constables (*Fairhaven Star*, 1 Dec. 1888; 15 Oct. 1898; 29 Oct. 1998; *Boston Daily Globe*, 1 Jan. 1896). In 1880, the Commonwealth of Massachusetts legislature passed an act to give the towns the right to regulate eels, *Anguilla rostrata*; clams; quahogs, *Mercenaria mercenaria*; and bay scallops, *Argopecten irradians irradians* within their waters. The town regulations were somewhat informal with the commonwealth being in formal control. In 1885, a closed season for scallops, from April until September, and a statewide limit of 25 bushels/person/day were established (Belding, 1910).

The *Fairhaven Star* and *Boston Daily Globe* newspapers list some actions by fish wardens and constables against violators in the late 1880's. The 1895 annual report of the town of Eastham listed the names of persons who held the title of "Fish Warden." They were elected at the annual Town Meeting. Their duties and responsibilities included overseeing the various fisheries in town including harvesting shellfish, the use of eel fykes, and herring runs. In 1899, the fish warden was paid $3.00 for the year.

### Legislation for Private Leasing

In 1904, the first state legislation regarding protection and cultivation of mollusks in Eastham, Orleans, and Wellfleet (Acts of 1904, Chapt. 270) was passed with several provisions:

1) A permit system for issuance to the residents was established;
2) A minimum size for quahogs, 1½ inches (38 mm) widest part, was set;
3) A limit of 1 bu/day for personal consumption and 1 bu/day for fish bait was established;
4) The selectmen could issue permits to "bed" quahogs on private leases, that had:
   a) a maximum of 75 ft $^2$;
   b) no shellfish already present on the beds;
   c) unobstructed natural navigable waterways.

Moreover the private rights of any person were not to be impaired. The penalties were a fine not more than $100, or 6 months imprisonment, or both.

The 1905 Eastham Annual Report reflects the acceptance by the town meeting of this statute as well as another entry which lists monies expended and "expenses to Boston on Quahog Act" (Anonymous, 1905). In 1906, the receipts for "oyster grants" were listed at $23.00 without reference to their number or location.

### Studies by David L. Belding

In 1905, the Massachusetts Commissioners of Fisheries and Game hired for

3 years a 21-year-old biologist named David L. Belding, a Williams College biology graduate, to conduct studies of the commercial mollusks and their fisheries in the state. Belding performed most of his work on the Lower Cape, principally in Wellfleet. He wrote a series of publications that described the biology and individual fisheries of quahogs, softshell clams, bay scallops, and oysters throughout the state (Belding, 1909a,b; 1910, 1912, 1931). The shellfishing bays and the numbers of fishermen, boats, types and value of gear, and economics were included. Belding's work became the cornerstone for the understanding of the natural history of the commercial mollusks and the overview of the molluscan fisheries in Massachusetts.

Belding reported that the history of management had consisted largely of closing beds to harvesting with little attention paid to propagation efforts. In the introduction to his quahog booklet (Belding, 1912), he called for seeding the public flats by the various towns and the state as well as the introduction of more private "grants," now know as "aquaculture lease sites."

Belding (1909a) discussed the possibility that mollusks would be depleted if an unlimited number of fishermen were allowed to harvest them, and he described the laws of supply and demand which produced enormous fishing pressure on the mollusks when the demand was high and prices were good. Belding apparently felt that the large number of boats (100) in the Wellfleet quahog raking fleet was threatening the stocks. He strongly supported the concept of local control and town rule of the beds, and he believed that the private cultivation of shellfish was required to sustain the fisheries. To him, this would involve the planting of seed shellfish on the beds if the abundances of various species were to remain as commercially viable.

Belding also documented the economic viability of the aquaculture industry and argued for many management strategies which are still valid today. They include: 1) planting spawners on beds to assist nature in increasing the supply of seed, 2) informing the fishermen about the importance of seed so they will not take it from the beds, 3) doing away with soaking bay scallop muscles in fresh water to swell them before marketing, 4) providing better cooperation between commission merchants and fishermen, and 5) increasing the popular demand for shellfish by improving transportation facilities and advertising them as good foods. Belding did not consider increasing the abundances of the mollusks by improving the condition of their habitats, i.e. controlling predators, spreading shells to collect oyster spat, or planting eelgrass on bare bottoms. This concept of improving habitats has been used in other states to enhance abundances of oysters.

## Reducing State Limits on Bay Scallop Harvests

The Massachusetts oyster and softshell clam fisheries were well established throughout the 1800's, but the quahog and bay scallop fisheries were relatively undeveloped until that century's last quarter. In the 1870's, fishermen began digging quahogs with long-handled rakes from their anchored catboats and taking bay scallops with hand dredges from sailing catboats. The numbers of days and hours each week that the catboats could harvest scallops was limited by weather conditions because the winds were irregular: catboats could not work during calm or stormy days.

The state allowed a daily limit of 35 bushels/boat to be taken, a quantity sufficiently large to enable the fishery to be profitable even though the number of harvesting days in a week might be limited. Shortly after 1900, the fishermen were installing engines in their catboats, enabling them to dredge for the scallops many more days and also in more locations. So, in 1909, the daily harvest limit was reduced to 10 bushels/man and no more than 20 bushels/2-man boat. During afternoons when the boats were returning from the beds with the shellfish, the shellfish wardens walked along their waterfronts to make sure the fishermen had not exceeded that limit or had not taken seed. This limit remains in effect today (Mass. General Laws, Chapt. 130, Sect. 72).

By the mid 1920's, Massachusetts towns were regulating their own molluscan fisheries informally with little influence from the state. For example in Eastham, the voters "left the disposition of the shellfishery in the hands of the Selectmen." (Belding, 1910).

The company Cape Cod Oyster Farms[2] held leases in the 1920's that totaled some 350 acres in Eastham waters. The town charged them an annual rental fee of $1.47/acre. On public beds, annual shellfish licenses were issued to the commercial harvesters for either the "flats" at a fee of $1.00 or the "bay" at a fee of $5.00. Requests for dredging in Cape Cod Bay were reviewed by the selectmen but not necessarily permitted. From 50 to 60 "bay" permits were issued annually.

## Town Control: Shellfish Constables in the Towns

About 25 years after Belding's publications, the State Legislature established a statewide protocol for the protection and propagation of the shellfishery. This came in the form of Chapter 329 of the Acts of 1933, which established what is now known as Chapter 130 of the General Laws of Massachusetts. The overall control of shellfisheries, then under the auspices of the State of Massachusetts, was transferred to each town. Massachusetts then had 78 coastal cities and towns (Anonymous, 2004), of which 56 were involved with shellfisheries (Fig. 1). If, by the vote of a town meeting, a town adopted the provisions of the law, the selectmen could then establish rules and provide for the designation of a shellfish constable (elected or appointed) "for the detection and prosecution of violations of the laws of the commonwealth or local ordinances, rules or regulations relative to shellfish or shellfisheries." This is the first time in the legislation that the term "constable" is formally identified. Considerable authority was given to this position.

[2]Mention of trade names or commercial firms does not imply endorsement by the National Marine Fisheries Service, NOAA.

The shellfish constable and also coastal wardens and the State Director of Marine Fisheries were given the power to search any boat, vessel, or vehicle without a warrant where there was probable cause to believe a rule violation was involved. This authority remains in place to this day, and it is remarkable because it permits such searches without an official government warrant.

The early shellfish constable was a citizen of his town and the town paid his salary. He knew the fishermen and their families. In the 1940's and 1950's, most constables were men in their 50's and older and most had been shellfishermen. They did not wear a uniform (Fig. 4). During the 1930's, the towns had reduced the daily scallop limit to between 3 and 7 bushels/person/day; the quantity varied among the towns. The purpose was to lengthen the scallop season so fishermen would earn incomes for a longer time each season during the 1930's economic depression. The reduced limits have remained in effect.

The town of Eastham adopted the provisions of Chapter 130 at a town meeting on 1 Feb. 1937—some 5 years later. The article which provided for that action also directed that the townspeople elect a "shellfish constable." An article was passed to appropriate the sum of $300 each year to pay the shellfish constable who was required to work a minimum of 600 hours during the year. In addition, the sum of $350 was appropriated for expenses including the transplanting of seed shellfish. The town also had three fish constables who presumably continued to enforce regulations concerning the finfish.

Figure 4—Top: Shellfish constable, locally referred to as "fish warden," in Edgartown supervising the opening of Edgartown Great Pond to the Atlantic Ocean, in about 1950. Bottom: Bulldozer digging a channel through South Beach to open Edgartown Great Pond to the Atlantic Ocean, about 1950. During that period, the pond was opened once a year and in the spring. The purpose was to increase the salinity of the pond's water and thus allow softshell clams to grow and fatten. Nowadays, the pond is opened 2–3 times a year for the benefit of the clams and also oysters.

By 1940, the town had established a so-called family shellfish permit, and in that year issued 500 such permits at $1.00 each and 30 commercial permits at $2.00 each. Many other revisions to the statute relative to the duties of shellfish constables have been made, including the addition of enforcement of the lobster regulations. The 1937 Act marked a distinct departure from shellfish management in many other coastal states, where there was no local management control and all the enforcement and propagation efforts are undertaken by either the state or county government.

Belding was also concerned about pollution contaminating shellfish growing waters. A revision to Chapter 130, passed by the state in 1941, provided for penalties for those persons who were found polluting waters in which shellfish were growing. The State Legislature also established a purification plant in 1928 in Newburyport to treat clams harvested from those areas before they were put on the market (Anonymous, 2004).

### The Shellfish Constable's Duties

During the late 1880's and through most of the 1900's, the primary function of the shellfish officers was to enforce regulations. A main goal of the management laws was to assure equitable harvests of the molluscan crop for as many people as possible. The officer made sure that all fishermen had licenses and did not harvest 1) out of season, 2) at night, 3) more than the town daily limit, and 4) take seed from the beds (Fig. 5).

The limit rule was one of the most difficult to control, especially with bay scallops, because they can be easy to

harvest and conceal. The constables also have served as herring (alewife), *Alosa pseudoharengus*, wardens if herring runs are present in their towns. They strive to maintain the runs in good condition between the marine waters and the freshwater ponds for the fish, and they enforce catch regulations.

Fishermen have purchased their shellfishing licenses at the town clerk's offices. When the season for a shellfish species begins, the shellfish constable obtains a list of people who own a commercial or a recreational shellfish license from this office, and then surveys the beds from shore or by boat to determine whether all persons have licenses. Constables are "user friendly" and allow fishermen without a license to purchase them before they go again without making a formal charge. A "good" constable has been regarded as one who was consistent and applied the law firmly but without discrimination.

The percentage of violations was probably low in earlier years because the shellfishing communities were "more closed" then. Within a town, the violation of any law, such as stealing property, was rare among its citizens, because such an act could bring considerable shame to him and his family. It was also rare for a town shellfisherman to violate a regulation. During a harvesting season, most fishermen rarely saw the town shellfish officer. The fishermen also regulated one another to an extent by challenging a persistent violator.

In recent years, an average of 25% of commercial fishermen throughout the State of Massachusetts commits some violation, mainly harvesting without possessing a license, harvesting in a closed area, or taking seed, in a given year. Penalties for violations include fines and suspensions of licenses (Sherman[3]).

The town shellfish constables have an office, commonly shared with the harbor master or environmental officer. The office is usually located in the town hall or in a small building at a town dock.

Figure 5.—Edgartown shellfish constable or "fish warden" holding a seed bay scallop he found in the harvest of a scalloper unloading at a shore of Sengekontacket Pond. Massachusetts allows no more than 3% seed, by count but not volume, in relation to the total scallops landed by fishermen. Fishermen rarely take many seed because they are easy to separate from the larger fully-grown scallops they sell.

He reports to the town's selectmen or the town shellfish board (if one exists), to describe his activities and problems about once a month.

One of his duties is to estimate the daily landings of each shellfish species. He does this by observing the numbers of fishermen on each of the beds and estimating the quantities of mollusks, by species, each will harvest. He maintains daily log sheets, and at the end of each year he adds up the totals and sends them to the State Division of Marine Fisheries (DMF) office, which then tallies the totals from each constable to determine the state landings for the year. State officials regard the totals that the constables submit each year as only rough estimates of actual landings, because the constables cannot monitor all the landings. The data are kept on file in the state office and a copy is sent to NOAA's NMFS, Fisheries Statistics Office in Silver Spring, Md. Annual landings records have been maintained from 1880 to the present (Table 2), and they are available to researchers and the general public.

Each Massachusetts town has bays of different sizes and also environments. Their predominant species could be oysters, softshell clams, quahogs, bay scallops, or various combinations of each. The conditions are so variable that local knowledge is a critical part of the successful implementation of any regulatory or conservation effort. Thus, the shellfish constable in each town has had to pursue his own approach to management. The towns gradually saw the need for deputy shellfish constables who are employed either part- or full-time.

## The MSOA

During the late 1950's and early 1960's, an awareness developed that estuaries needed to be "healthy" to continue to produce mollusks and be good nurseries for juvenile finfishes. Various research studies and popular

[3]Sherman, G. President of the Massachusetts Shellfish Officers Association and Shellfish Constable, Town of Westport, Mass. Personal commun., 2008.

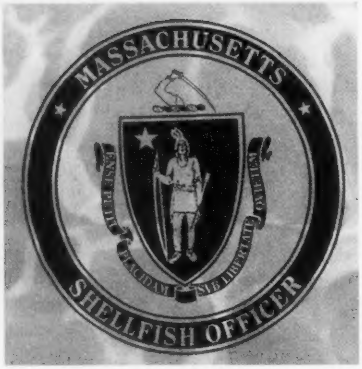



Figure 6.—Emblem of the Massachusetts Shellfish Officers Association.

Table 2.—Landings in bushels of the most important estuarine mollusks in Massachusetts, every 25 years, 1900–2000. Data were collected by shellfish wardens and constables.

| | Mollusks | | | |
|---|---|---|---|---|
| Year | Northern quahog | Softshell clam | Bay scallop | Oyster |
| 1900[1] | 71,000 | 175,000 | 100,000 | 93,000 |
| 1925[1] | 138,000 | 138,000 | 206,000 | 86,000 |
| 1950[1] | 168,000 | 117,000 | 164,000 | 33,000 |
| 1975[2] | 93,000 | 86,000 | 275,000 | 8,700 |
| 2000[2] | 123,000 | 46,000 | 4,120 | 1,300 |

[1] Source: Lyles, 1969.
[2] Source: NMFS Annual Landings Statistics.

literature were documenting that salt marsh habitats were valuable nurseries and sources of nutrients in estuaries, and they described how important estuarine systems were being destroyed by dredging and filling.

Shellfish constables were aware of the pressing need to preserve the estuarine habitats, and they collaborated with legislators to produce a series of "Estuarine Reports," which spanned from 1965 through the early 1970's, that named all the major estuaries of the state with an emphasis on the need for legal protection of their wetlands (Jerome et al., 1968). Subsequently, a law, known as the Jones Law, was enacted to protect estuarine environments from wholesale demolition of wetlands and shellfish beds. This important step was the catalyst that resulted in the formation of the Massachusetts Shellfish Officers Association (MSOA), a loose association of constables with an elected Board of Directors and a President. The MSOA was formed during the 1970's and was officially incorporated in 2000 with a filing with the State of Massachusetts Secretary of State and Attorney General.

Since the MSOA has been organized, ideas and successful techniques can be effectively shared, and collaborations among towns are possible. As a symbol of continuity, the constables are encouraged to wear a standardized green jacket and cap with an official emblem on them (Fig. 6). Meetings of the constables have been held every 3 months. They are in different towns each time so that some constables have a shorter distance to travel to at least one of the meetings each year. From 40 to 50 constables or deputy constables attend each meeting, driving from their towns early in the morning and returning home in the evening.

The meetings allow the constables to interact socially, discuss topics of common interest, hear lectures from state officials and biologists, and have a noontime meal. The DMF has been an integral part of the group, and 2–4 of its officials participate in each meeting and contribute a wider perspective. Officers of the State Environmental Law Enforcement Division, who initially were referred to as Coastal Wardens and are currently organized as the Environmental Police, also have participated and have provided new information at the meetings.

The mission of the Environmental Police is to protect the bays and shorelines, and enforce the regulations for finfisheries, lobsters, boating safety, and all hunting laws. Shellfish constables cooperate with them, watching for violations and assisting in some prosecution actions that they may not be specifically authorized to enforce. Increasingly, in this era of homeland security issues, the shellfish constable also assumes the additional role as observer of suspicious activity along waterfronts and in the bays.

In 1972, a previously unrecognized event changed the landscape of shellfish management when blooms of a red tide-producing organism appeared in some bays. Paralytic shellfish poisoning (PSP) phytoplankton was present and it spread across wide areas as the result of a late season hurricane. Bays containing red tides were closed to harvesting, and this marked the beginning of another phase of management of the shellfish constables.

A program for regular monitoring of the shellfish beds for the red tide organism was established and the local constables were called to assist with weekly sampling of shellfish for analysis. The program continues to the present. When beds are closed to harvesting, the constable must post the area and patrol it every day to ensure that no person either knowingly or accidentally harvests any shellfish. As a result, there have been no reported instances of PSP health issues in the state.

## Enhancing Mollusk Populations

In the early 1970s, several shellfish hatcheries in the state began to produce seed, mainly quahogs, for private aquaculturists (Fig. 7). As Belding's wise words were being assimilated and his forecasts became reality, growers were realizing that profitable farming of quahogs in bays was possible. Some towns purchased quahog and bay scallop seed for their public beds. Their constables grew it to larger sizes, and then broadcast it onto the beds (Fig. 8). This introduction of seed would not replace a bountiful natural set but might enhance abundances to counter the depletions from harvesting and the degrading of water quality.

The MSOA members also became aware of the value of political involvement. To that end, a group of legislators who represented the coastal cities and towns formed a group known

**The following are two annual reports of the shellfish officers in the town of Edgartown for the years 1962 and 2004. The officer, termed Fish Warden in 1962, did not have a staff, and he dealt with enforcing regulation and propagation using wild seed and adults. He removed and destroyed horseshoe crabs, but currently they are a protected species.**

**The officer in 2004, then termed Shellfish Constable, had a staff of 2 permanent deputies and 2 summer deputies. He dealt with enforcing regulations, probations using hatchery seed, and was active in monitoring environmental conditions. There was more recreational shellfishing recorded in 2004 than in 1962.**

### Report of the Fish Warden for the year 1962

(Source: Town of Edgartown Annual Report for 1962)

The shellfisheries of Edgartown valued nearly $68,622 during 1962. The following is a breakdown of the shellfish taken by species.

| Shellfish | Bushels | Value |
|---|---|---|
| Scallops | 9,946 | $53,428 |
| Softshell clams | 1,251 | 12,510 |
| Quahogs | 355 | 2,684 |

A total of 528 licenses were issued in 1962 as follows:

126 commercial scallop licenses
19 commercial soft clam licenses
17 commercial quahog licenses
366 family permits, seasonal and resident

1. 240 chicken wire bags each containing 1.5 bushels of scallop shells were made up and 500 bushels of scallop shells were planted in Edgartown Great Pond as oyster cultch.
2. 147 bushels of seed oysters were obtained from Wareham and planted in Great Pond.
3. 100 bushels of small quahogs were obtained from the state and planted in Pocha Pond.
4. 20 bushels of seed quahogs were moved from Wasque Pond and planted in Anthier's Pond, Eel Pond, and Edgartown Harbor.
5. Seed and adult oysters exposed after the opening of Great Pond were moved into deeper water.
6. Bi-weekly records were maintained of the temperature and salinity of Great Pond to determine what conditions appeared favorable or unfavorable for oyster spawning and setting.
7. 78 bushels of clams were obtained from the Oyster Pond and Great Pond and planted in Anthier's Pond, Eel Pond, and Caleb's Pond.
8. Horseshoe crabs and starfish were destroyed wherever observed.

Four violations of shellfish regulations were reported to the selectmen resulted in disciplinary action. Generally speaking, the cooperation of the fishermen in supporting the regulations has been excellent.

The shellfish officer has continued to work in cooperation with the Massachusetts Division of Marine Fisheries in his efforts to promote the shellfishing industry of Edgartown.

I would like to express my thanks to Mr. John Hughes and Dr. George Matthiessen for all the help they have given me since my appointment as Fish Warden.

Hiram Jackson
Fish Warden

### Summary of the Shellfish Constable's Annual Report to the Town of Edgartown, 2004

(Source: Town of Edgartown Annual Report, 2004)

To the Honorable Board of Selectmen and Citizens of Edgartown:

The 2004 commercial catch in Edgartown was valued at $264,167 in the following categories:

| | | |
|---|---|---|
| Softshell clams | 401 | bushels |
| Oysters | 336 | bushels |
| Quahogs | 182 | bushels |
| Bay scallops | 1,552 | bushels |

Severe weather in January and February and a small crop of scallops in November and December led to a poor commercial crop year in the town of Edgartown. Cape Poge Pond had the most scallops this year and has some seed for next year. Recreational scallopers were able to harvest scallops out of the shallow areas of Cape Poge. Family fishermen found a limited number of scallops in Sengekontacket (Anthiers). We are cautiously optimistic about a good scallop crop for the 2005–2006 season. Commercial oystering and quahoging were limited by market situations this year, most harvests were sold in local fish markets.

In addition to the wild harvest, aquaculturists in Edgartown have raised 625 bushels of oysters worth $162,500.

These are the landings for recreational permit holders:

| | |
|---|---|
| Softshell clams | 106 bushels |
| Oysters | 65 bushels |
| Quahogs | 598 bushels |
| Bay scallops | 81 bushels |

Shellfish received from the Martha's Vineyard Shellfish Group are as follows:

| | |
|---|---|
| Quahog seed | 1,200,000 |
| Large scallop seed | 187,500 |
| Small scallop seed | 1,300,000 |
| Single oyster seed | 334,000 |

All hatchery-reared bay scallops were broadcast in Sengekontacket Pond and Cape Poge Pond. As in the past, some of these scallops were genetically tagged with black and white stripes. The oysters that we received were placed in nursery up-weller for growth out to 15 mm.

The Shellfish Department continues to monitor shellfish diseases within town waters. Despite substantial softshell clam mortality among adults in Edgartown Great Pond in 2002 and 2003, we had a decent softshell clam harvest on Edgartown Great Pond in 2004.

In 2004, Edgartown participated in several water quality monitoring programs. The Massachusetts Estuaries Program is an ongoing study of Edgartown Great Pond that will be completed in 2005. The intent of this study is to better understand nutrient cycling within the watershed.

The following predators were removed from shellfish areas in Edgartown:

| | |
|---|---|
| 983 | pounds of conchs from Cape Poge |
| 2,300 | conch egg cases from Cape Poge |
| 800 | pounds of conchs from Katama Bay |
| 5,600 | conch egg strands from Katama Bay |
| 200 | pounds of conchs from Sengekontacket |
| 8,940 | pounds of green crabs from Sengekontacket |

The shellfish Department continues to work with the Dredge Committee on permitting various dredging projects.

Personnel in 2004 included Department Head/Marine Biologist Paul Bagnall and full-time Deputy Warren Gaines. Full-time deputy David Medeiros resigned in May and was replaced by Francis Fisher III. Summer Deputies were John Black and Matthew Hedstrom.

Respectfully submitted,

Paul L. Bagnall
Marine Biologist and Shellfish Constable
Herring Warden

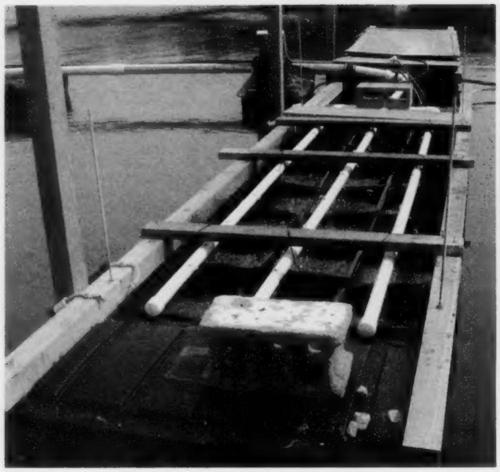


Figure 7.—A float in Eastham serves as a nursery for growing northern quahog seed.

Figure 8.—A net over an intertidal flat in Eastham protects northern quahog seed from predaceous crabs.

as the "Coastal Caucus." This group was instrumental in cooperating with the MSOA to craft legislation which provided for additional funding for towns that wished to participate in efforts to protect and propagate shellfish—the so-called 571 Fund. The requirement was that the towns had to develop a management plan for their shellfisheries. The amount of funds would be based on the previous year's expenditure.

This program was initially set at direct funding but as more towns began to participate the percentage diminished. The program was a wholesale effort by cities and towns to plan and implement various projects which would enhance the fishery. Some towns used hatchery seed while others transplanted abundant shellfish stocks from polluted beds that were not certified as clean for harvest to clean beds (Fig. 9a, b). The shellfish depurated naturally and the beds could be opened for harvesting after 90 days. Over time, many thousands of bushels of quahogs and oysters were relayed from polluted areas along Massachusetts' south coast to the beds of various towns to boost their stocks.

Figure 9a.—Shellfish constables and helpers in Chatham transplanting bay scallops that had been washed ashore by a storm to a replanting site.

In 1974, the Barnstable County government of the towns on Cape Cod began an initiative to encourage cooperation among the towns. The County Commissioners formed a Shellfish Advisory Committee (SAC), that provided reports to the commissioners and was assisted by the Cape Cod Economic Development Commission. Later on, the University of Massachusetts Cooperative Extension Service began to support the SAC by providing staff and resources to assist in the various towns' propagation plans. An alliance with the Woods Hole Sea Grant program together with funding from the state Environmental Bond Bill provided additional funding for regional aquaculture centers that would serve to guide the increasing needs of private aquaculturists and those towns involved with nursery growout of seed shellfish for restocking, disease testing,

Figure 9b.—(above left) Shellfish constables in Westport supervising the transplanting of quahogs from polluted waters to clean waters.

Figure 10.—(below left) Shellfish constable showing youngsters aspects of quahog reproduction.

Figure 11.—(above right) Shellfish constable collecting sample of surface water to be examined for pollution.

predator control, public outreach, and other programs (Fig. 10).

In 1987, Massachusetts reorganized some of its agencies in response to Federal requirements for the inspection and classification of waters from which shellfish were harvested. The duties and responsibilities relative to testing water and the classification of areas in accordance with Federal standards were assigned to the DMF, which turned to local shellfish constables for assistance. Since then, regular monitoring of surface waters has been carried out by state personnel and the constables working together (Fig. 11). The authority to declare a body of water "approved" for the harvest of shellfish or "contaminated" and thus closed to the harvest of shellfish remains with the DMF. Enforcement of the regulations is carried out by the local constables with assistance from the Environmental Police.

The shellfish constables also frequently try to control sources of pollution that might result in an area being closed to shellfish harvesting. This can involve working with public works agencies to remediate storm drains, promote bylaws to restrict the feeding of waterfowl, and assist local Boards of Health to hold and, if possible, reverse a disturbing trend. Recent actions by the constables in the towns of Barnstable and Dennis have resulted

in the reopening of shellfish resources in waters that had remained closed for harvesting for the past 20 years.

In 1990, multiple failures of different hatcheries resulted in few seed being available for the different towns. The constables explored various alternatives cooperatively and the outcome was that the funding received by the DMF was channeled to the towns through the Barnstable County Extension Service by way of bulk purchases of hatchery seed. In this way, less expensive seed could be obtained and its availability would be more certain.

## Training Program for Constables

Successful protection of the molluscan resources and aquatic environments has been under increasing strain as humans have crowded onto coastal Massachusetts. It became apparent that a standardized training program for constables was needed. An agreement was reached with the Massachusetts Maritime Academy in the town of Buzzards Bay to provide a 2 week training session for shellfish constables and deputies. Conducted on the campus of the academy when the cadets are at sea on training cruises and as the need arises, this course is a comprehensive examination of the biology, natural history, and harvesting methods of various shellfish as well as their predators, and it encompasses training in law enforcement, boat handling, first responder measures, pollution monitoring, and on the red tide phenomenon.

## Overview

Today's Massachusetts shellfish constable has a more complex and varied role than had his predecessors. The warden's main responsibility once was to enforce a few regulations regarding the harvests of the mollusks. The constable today also has to be aware of legal matters, environmental concerns, natural history, and law enforcement regulations. He or she should also be personable and have the ability to work on and near the water under various weather conditions. He has the satisfying role of being the steward of his town's molluscan resources and environment and a promoter of its commercial and recreational shellfisheries.

## Literature Cited


Anonymous. 1905. Town of Eastham Annual Report for 1905.

Anonymous. 2004. The Acts and Resolves of 1928, General Laws of Massachusetts.

Belding, D. L. 1909a. A report upon the mollusk fisheries of Massachusetts. Wright & Potter Printing Co., State Printers, Boston, 243 p.

________. 1909b. The soft-shelled clam fishery of Massachusetts. Commonw. Mass., Mar. Fish. Ser., 1, 65 p. (republ. in 1916 and 1930).

________. 1910. A report upon the scallop fishery of Massachusetts, including the habits, life history of *Pecten irradians*, its rate of growth, and other facts of economic value. Wright and Potter Printing Co., State Printers, Boston, 150 p.

________. 1912. The quahaug fishery of Massachusetts, including the natural history of the quahog and a discussion of quahog farming. Commonw. Mass., Mar. Fish. Ser. 2, 41 p.

________. 1931. The quahog fishery of Massachusetts. Mass. Dep. Conserv., Div. Fish. Game, Mar. Fish. Serv. 2, 41 p.

Jerome, W., A. Chestmore, and C. O. Anderson, Jr. 1968. A study of the marine resources of the Parker River-Plum Island South Estuary. Monograph by the State of Mass., Div. Mar. Fish.

Ingersoll, E. 1887. The oyster, scallop, clam, mussel, and abalone industries. The Scallop Fishery. *In* G. Brown Goode (Editor), The fisheries and fishery industry of the United States. Sect. V, Vol. II, p. 565–581, U.S. Gov. Print. Off., Wash., D.C.

Lyles, C. H. 1969. Historical catch statistics (shellfish). U.S. Dep. Interior, Fish Wildlife Serv., Curr. Fish Stat. 5007, 116 p.

Pratt, E. 1844. A comprehensive history, ecclesiastical and civil of Eastham, Wellfleet and Orleans, County of Barnstable, Mass. W. S. Fisher and Co., Publ., 180 p.

Rider, R. A. 1989. Life and times in Wareham over 200 years 1739–1939. W. S. Sullwold Publ., Inc. Tauton, Mass., for the Wareham Hist. Soc., 228 p.

# Editorial Guidelines for the *Marine Fisheries Review*

The *Marine Fisheries Review* publishes review articles, original research reports, significant progress reports, technical notes, and news articles on fisheries science, engineering, and economics, commercial and recreational fisheries, marine mammal studies, aquaculture, and U.S. and foreign fisheries developments. Emphasis, however, is on in-depth review articles and practical or applied aspects of marine fisheries rather than pure research.

Preferred paper length ranges from 4 to 12 printed pages (about 10-40 manuscript pages), although shorter and longer papers are sometimes accepted. Papers are normally printed within 4-6 months of acceptance. Publication is hastened when manuscripts conform to the following recommended guidelines.

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Submission of a manuscript to the *Marine Fisheries Review* implies that the manuscript is the author's own work, has not been submitted for publication elsewhere, and is ready for publication as submitted. Commerce Department personnel should submit papers under a completed NOAA Form 25-700.

Manuscripts must be typed double-spaced throughout and submitted with two duplicate copies. The complete manuscript normally includes a title page, a short abstract, text, literature citations, tables, figure legends, footnotes, and the figures. The title page should carry the title and the name, department, institution or other affiliation, and complete address (plus current address if different) of the author(s). Manuscript pages should be numbered and have 1-inch margins on all sides. Running heads are not used. An "Acknowledgments" section, if needed, may be placed at the end of the text. Use of appendices is discouraged.

### Abstract and Headings

Keep titles, headings, subheadings, and the abstract short and clear. Because abstracts are circulated by abstracting agencies, it is important that they represent the research clearly and concisely. Headings within each section must be short, reflect a logical sequence, and follow the rules of multiple subdivision (i.e. there can be no subdivision without at least two items).

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The entire text should be intelligible to interdisciplinary readers; therefore, all acronyms, abbreviations, and technical terms should be spelled out the first time they are mentioned. The scientific names of species must be written out the first time they are mentioned; subsequent mention of scientific names may be abbreviated. Follow the U.S. Government Printing Office Style Manual (1984 ed.) and the CBE Style Manual (5th ed.) for editorial style, and the most current issue of the American Fisheries Society's Common and Scientific Names of Fishes from the United States and Canada for fish nomenclature. Only journal titles, scientific names (genera and species), and vessel names should be italicized. Dates should be written as follows: 11 Nov. 1991. Measurements should be expressed in metric units, e.g. metric tons as t; other equivalent units may also be listed in parenthesis. Common abbreviations and symbols such as mm, m, g, ml, mg, and °C (without periods) may be used with numerals. The numeral one (1) should be typed as a one, not as a lowercase el (l). Write out the numbers zero through nine unless they form part of measurement units (e.g. nine fish but 9 mm).

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Figures include line illustrations and photographs (or slides) and must be cited in numerical order in the text. Figures are to be labeled with author's name and number of figure. Use Times Roman font (upper and lowercase letters) to label within figures. Avoid vertical lettering except for y-axis labels. Zeros should precede all decimal points for values less than one. Figures should be submitted as both laser-printed copies and computer software files. Figure legends should explain all symbols and abbreviations and should be double-spaced on a separate page at the end of the manuscript. Consider column and page sizes when designing figures. Please note that we do not print graphics in color.

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